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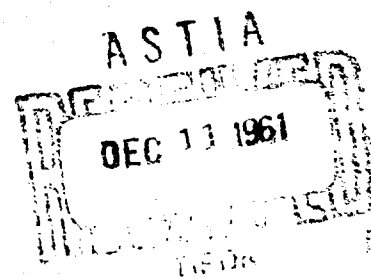
WADD TECHNICAL REPORT 60-325

A Manual of Materials for Microwave Tubes

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RADIO CORPORATION OF AMERICA

JANUARY 1961



WRIGHT AIR DEVELOPMENT DIVISION

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A Manual of Materials for Microwave Tubes

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January 1961

Electronic Technology Laboratory

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Task No. 41533

Wright Air Development Division
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by the Radio Corporation of American, Harrison, New Jersey, on Air Force Contract No. AF33(616)-6563, under Task Nr 41533 of Project Nr 4156 "High Temperature Microwave Tube Design and Processing." The contract efforts were accomplished under the cognizance of the Electronic Technology Laboratory, Wright Air Development Division (formerly Wright Air Development Center), with the technical work directed by Richard P. Firsdon as task engineer.

The material was assembled by D. L. Thornburg, E. S. Thall, and Dr. J. Brous of the Chemical and Physical Laboratory of the RCA Microwave Tube Operations at Harrison, New Jersey. Dr. Brous also prepared the section on Cathode Poisoning. Mr. A. L. Balber of Microwave Engineering Technical Publications contributed to the organization and the format of the manual.

ABSTRACT

This manual presents a compilation of data and information on the properties of twenty-two materials considered important in the design of high-temperature microwave tubes. Also included is a discussion of the poisoning effects of gases and metallic vapors on thermionic emitters of various types.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:



AMOS H. DICKE
CHIEF, Thermionic Branch
Electronic Technology Laboratory

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SECTION I

INTRODUCTION

This manual has been prepared under Contract No. AF33(616)-6563 "High Temperature Microwave Tube Design and Processing".* This program has been concerned with physicochemical properties of a number of materials selected because of present or potential importance to the design of microwave tubes for high temperature operation. The manual includes, in addition, a number of materials not included in the experimental phase of the program which are also considered important to microwave tube design.

The materials covered in this manual do not, however, represent a comprehensive selection of all materials either of present or potential importance (such a survey is beyond the scope of this program), but rather a limited list of those materials which may be most frequently encountered in present microwave tube designs.

Furthermore, some materials such as 403 Monel, Inconel, and several stainless steels were chosen as representatives of their class of materials. It was considered that specific information for specific alloys would prove more useful and in line with the scope and magnitude of the program than a collection of broad generalizations concerning classes of materials. It

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should not be inferred, however, that the listing of an alloy in this manual recommends its choice over any other material of its type.

The information has been organized under the following captions:

1. Name of Material
2. Chemical Composition
3. Trade Designations
4. Suppliers
5. Forms Available
6. Description
7. Special Handling Techniques
8. Joining
9. Applications
10. Data Sheet
11. Graphs

The first five items are self-explanatory.

Item 6 "Description" is of a general nature and attempts to acquaint the reader with the general properties of the materials.

Item 7, "Special Handling Techniques", indicates methods of forming and handling. Here also, are listed the various difficulties which may be encountered because of the special nature of the material. For example, reactive materials such as titanium or those which may be prone to hydrogen or sulfur embrittlement must be handled with special precautions. Where possible, these precautions are given.

Item 8, "Joining", is a brief discussion of methods found useful in joining the subject material either to itself or to other materials. The data enumerated here have been obtained from literature sources as well as from discussions with shop personnel and assembly technicians who have been directly involved with brazing, welding or other methods of joining.

The applications listed in Item 9 are those which have already been proven in practice. This listing may help engineers decide on the feasibility of a particular application for that material.

The data sheet for each material lists general properties useful in design.

Several graphs form a portion of the report on each material. The data used in plotting these graphs were obtained from various literature sources as well as from work done in this laboratory.

The information found in the literature was by no means complete or consistent for materials. Undoubtedly there are also published data which have not been uncovered in the literature search. This manual, therefore, represents as much reliable and valuable information as could be found and organized.

In another section of the manual are charts showing variations of properties with temperature for a number of materials. This permits a rapid comparison of several materials for a single property.

Another section deals with the thermionic emission of various cathode types and the effects of gases or metal vapors.

Some further remarks are in order concerning some of the functions reported in this manual.

Thermal Emission - The thermal emission constants given in this report are based upon literature values. They indicate the ratio of emission of the given material to a perfect black-body radiator at the wavelength and temperature noted. Surface conditions such as roughness, oxidation, etc. can cause large changes in emissivity.

Thermionic Emission - The equation relating thermionic emission to temperature may be written as $\log I = \log A + 2 \log T - \frac{5034 \phi}{T}$. Examination of the equation indicates that a straight line will be obtained if we plot $\log \left(\frac{I}{T^2} \right)$ versus $\frac{1}{T}$. In this report, however, $\log I$ has been plotted directly against reciprocal temperature for convenience of use. The variation in the term $\frac{5034 \phi}{T}$ is so much greater than the variation in $2 \log T$ that within the limits of accuracy imposed by the graph, a straight line is obtained.

Expansion - Literature values are given for linear thermal expansion. Mean and total values between room temperature and indicated temperature are given where available. Total expansion corresponds to $\frac{\Delta L \times 10^3}{L}$ and mean expansion is given by $\frac{\Delta L \times 10^6}{L \times \text{OC}}$.

Resistivity - Electrical resistivity versus temperature has been plotted for some materials using data from literature sources. It should be

noted that impurities and previous history of the specimen will have a large influence on the electrical resistivity.

Dielectric Constant and Loss Factor - Dielectric constants and loss factors are reported for the two ceramic materials covered in this report. Alumina and forsterite, if reasonably pure, are both quite good from the viewpoint of high frequency applications at high temperature but physical properties may vary from one batch to another or between different manufacturers.

Vapor Pressure - Vapor pressure values have been obtained from various sources and in some instances have been calculated from constants such as those given by Dushman⁴ and Smithells⁷. Some determinations were also made in this laboratory of alloy vapor pressures. Judging from reference works and from work carried on in this laboratory it would appear that prediction by calculation of vapor pressure of minor elements is risky. For example, prediction of the vapor pressure of zinc in brass exceeds the observed vapor pressure by several orders of magnitude when the zinc content is reduced to about 1% or less. On the other hand, the same sort of approach would indicate a vapor pressure for chromium in Nichrome V of about one-fiftieth the measured value. It would be well, therefore, to determine the rate of evaporation of any material which is to be subjected to temperatures over 400°C in vacuum for long periods of time. Such a test could consist of heating a sample of the material which will be used in the design. The rate of weight loss of the sample will be related to its vapor pressure and an indication of its usefulness under specific application conditions can be obtained.

Evaporation Rate - Evaporation rates have in some cases been calculated from available data. Some information on alloys was determined in the course of this project. Vapor pressure is directly related to evaporation rate in vacuum and either value is indicative of relative volatilities of materials.

Tensile Strength - Tensile strength values were taken from the literature and are given for each of the materials where available. This property is often extremely sensitive to impurities as well as to the previous history of the specimen. The values given should be used with the understanding that in some cases they represent approximate values or a simple comparative ranking of the material.

Modulus of Elasticity - Young's modulus is commonly given for structural materials in physical property tables and may prove useful in design calculations where rigidity must be considered. Values are given as found in the literature.

Specific Heat - Specific heat values where available have been extracted from literature sources. The specific heats are useful in designing parts which may be subjected to temperature changes.

Gas Diffusion Rate - Gas diffusion or permeation rates were reported for those materials for which this information is available. Some of the values determined experimentally in this program were also included. Only values for hydrogen permeation were given for the materials studied in this

program since only hydrogen was found to diffuse measurably through the materials at temperatures up to 850°C.

SECTION II

DEFINITIONS

A list of definitions of some of the terms used in the manual is given below. These definitions were selected from a glossary of metallurgical terms given in the 1948 edition of "Metals Handbook" (pp 1-19) and are reproduced with the permission of the American Society for Metals.

Age hardening - A process of aging that increases hardness and strength and ordinarily decreases ductility. Age hardening usually follows rapid cooling or cold working. See aging.

Aging - In a metal or alloy, a change in properties that generally occurs slowly at atmospheric temperature and more rapidly at high temperatures. See also age hardening and precipitation hardening.

Alloy - A substance that has metallic properties and is composed of two or more chemical elements of which at least one is a metal.

Alpha iron - The form of iron that is stable below 910°C, and characterized by a body-centered cubic crystal structure.

Annealing - A process involving heating and cooling, usually applied to induce softening. The term also refers to treatments intended to alter mechanical or physical properties, produce a definite micro-structure, or remove gases. Where applicable, the following more specific terms should be used: bright annealing, full annealing, process annealing, stabilizing annealing. When applied to ferrous alloys, the term "annealing" without qualification, implies full annealing. Any process of annealing will usually reduce

stresses, but if the treatment is applied for the sole purpose of such relief, it should be designated as "stress relieving".

Annealing (nonferrous metallurgy) - A heat treatment designed to effect: (1) softening of a cold worked structure by recrystallization or grain growth or both; (2) softening of an age hardened alloy by causing a nearly complete precipitation of the second phase in relatively coarse form; (3) softening of certain age hardenable alloys by dissolving the second phase and cooling rapidly enough to obtain a supersaturated solution (this usage is generally applied to nickel-base and copper-base alloys; the treatment should be called more precisely a "solution heat treatment").

Arc welding - Welding accomplished by using an electric arc that may be formed between a metal or carbon electrode and the metal being welded; between two separate electrodes, as in "atomic hydrogen welding"; or between the two separate pieces being welded, as in flash welding.

Austenite - A solid solution in which gamma iron is the solvent; characterized by a face-centered cubic crystal structure.

Brazing - Joining metals by fusion of nonferrous alloys that have melting points above 425°C but lower than those of the metals being joined. This may be accomplished by means of a torch (torch brazing), in a furnace (furnace brazing) or by dipping in a molten flux bath ("dip" or "flux" brazing). The filler metal is ordinarily in rod form in torch brazing; whereas in furnace and dip brazing the work material is first assembled and the filler metal may then be applied as wire, washers, clips, bands, or may be integrally bonded, as in "brazing sheet".

Bright annealing - A process of annealing usually carried out in a controlled furnace atmosphere so that surface oxidation is reduced to a minimum and the surface remains relatively bright.

Bright dip - An acid solution into which articles are dipped to obtain a clean, bright surface.

Cold work - Plastic deformation at such temperatures and rates that substantial increases occur in the strength and hardness of the metal. Visible structural changes include changes in grain shape and, in some instances, mechanical twinning or banding.

Cold working - Deforming a metal plastically at such a temperature and rate that strain hardening occurs. The upper limit of temperature for this process is the "recrystallization temperature".

Creep - The flow or plastic deformation of metals held for long periods of time at stresses lower than the normal yield strength. The effect is particularly important if the temperature of stressing is in the vicinity of the recrystallization temperature of the metal.

Damping capacity - The ability of a metal to absorb vibrations, changing the mechanical energy into heat. See internal friction.

Deep drawing - Forming cup-shaped articles or shells by using a punch to force sheet metal into a die.

Fatigue - The tendency for a metal to break under conditions of repeated cyclic stressing considerably below the ultimate tensile strength.

Ferrite - A solid solution in which alpha iron is the solvent, and which is characterized by a body-centered cubic crystal structure.

Full annealing - A softening process in which a ferrous alloy is heated to a temperature above the transformation range and, after being held for a sufficient time at this temperature, is cooled slowly to a temperature below the transformation range. The alloy is ordinarily allowed to cool slowly in the furnace, although it may be removed and cooled in some medium that insures a slow rate of cooling.

Gamma iron - The form of iron stable between 910° and 1400°C characterized by a face-centered cubic crystal structure.

Heat treatment - A combination of heating and cooling operations, timed and applied to a metal or alloy in the solid state in a way that will produce desired properties. Heating for the sole purpose of hot working is excluded from the meaning of this definition.

Hooke's law - Stress is proportional to strain in the elastic range.

Hot working - Plastic deformation of metal at such a temperature and rate that strain hardening does not occur. The lower limit of temperature for this process is the recrystallization temperature.

Intermediate annealing - An annealing treatment given to wrought materials before fabrication to final gauge and final thermal treatment.

Internal friction - Ability of a metal to transform vibratory energy into heat. Internal friction generally refers to low stress levels of vibration; "damping" has a broader connotation since it may refer to stresses approaching or exceeding the yield strength.

Modulus of elasticity - The slope of the elastic portion of the stress-strain curve in mechanical testing. The stress is divided by the unit

elongation. The tensile or compressive elastic modulus is called "Young's modulus"; the Torsional elastic modulus is known as the "shear modulus" or "modulus of rigidity".

Modulus of rigidity - In a torsion test, the ratio of the unit shear stress to the displacement caused by it per unit length in the elastic range. This modulus corresponds to the modulus of elasticity in the tension test.

Natural aging - Spontaneous aging of a supersaturated solid solution at room temperature.

Normalizing - A process in which a ferrous alloy is heated to a suitable temperature above the transformation range and is subsequently cooled in still air at room temperature.

Ordering - A reaction or transformation in certain solid solutions in which a random arrangement of solvent and solute atoms in the crystal is replaced by a regular or ordered arrangement of the different atoms on preferred lattice sites. See superlattice.

Precipitation hardening - A process of hardening an alloy in which a constituent precipitates from a supersaturated solid solution. See also age hardening and aging.

Precipitation heat treatment - Any of the various aging treatments conducted at elevated temperatures to improve certain of the mechanical properties through precipitation from solid solution.

Process annealing - In the sheet and wire industries, a process by which a ferrous alloy is heated to a temperature close to, but below, the

lower limit of the transformation range and is subsequently cooled. This process is applied in order to soften the alloy for further cold working.

Proportional limit - The greatest stress that the material is capable of sustaining without a deviation from the law of proportionality of stress to strain (Hooke's Law).

Recovery - The removal of residual stresses by localized plastic flow as the result of low-temperature annealing operation; performed on cold worked metals without altering the grain structure or strength properties substantially.

Recrystallization - A process whereby the distorted grain structure of cold worked metals is replaced by a new, strain-free grain structure during annealing above a specific minimum temperature.

Recrystallization temperature - The lowest temperature at which the distorted grain structure of a cold worked metal is replaced by a new, strain-free grain structure during prolonged annealing. Time, purity of the metal, and prior deformation are important factors.

Relaxation - Relief of stress as the result of creep. Some types of tests are designed to provide diminution of stress by relaxation at constant strain, as frequently occurs in service.

Residual stress - Macroscopic stresses that are set up within a metal as the result of nonuniform plastic deformation. This deformation may be caused by cold working or by drastic gradients of temperature from quenching or welding.

Resistance welding - A type of welding process in which the work pieces are heated by the passage of an electric current through the contact. Such

processes include spot welding, seam or line welding and percussion welding. Flash and butt welding are sometimes considered as resistance welding processes.

Secondary creep - The second portion of the creep curve following the initial creep stage and in which the rate of creep has reached a rather constant value.

Solution heat treatment - A process in which an alloy is heated to a suitable temperature, is held at this temperature long enough to allow a certain constituent to enter into solid solution and is then cooled rapidly to hold the constituent in solution. The metal is left in a supersaturated, unstable state and may subsequently exhibit age hardening.

Spot welding - An electric-resistance welding process in which the fusion is limited to a small area. The pieces being welded are pressed together between a pair of water-cooled electrodes through which an electrical current is passed during a very short interval so that fusion occurs over a small area at the interface between the pieces.

Stabilizing anneal - A treatment applied to austenitic stainless steels that contain titanium or columbium. This treatment consists of heating to a temperature below that of a full anneal in order to precipitate the maximum amount of carbon as titanium carbide or columbium carbide. This eliminates precipitation at lower temperatures, which might reduce the resistance of the steel to corrosion.

Stabilizing treatment - A thermal treatment designed to precipitate material from solid solution, in order to improve the workability, to

decrease the tendency of certain alloys to age harden at room temperature, or to obtain dimensional stability under service at slightly elevated temperatures.

Strain - Deformation expressed as a pure number or ratio. (1) Ordinarily expressed as epsilon (ϵ), equivalent to the change in length divided by original length. (2) True strain (δ or ϵ) is the logarithm of the ratio of the length at the moment of observation, to the original length. True strain δ does not differ much from ϵ until above 20%.

Strain hardening - An increase in hardness and strength caused by plastic deformation at temperatures lower than the recrystallization range.

Stress - The load per unit of area. Ordinarily stress-strain curves do not show the true stress (load divided by area at that moment) but a fictitious value obtained by using always the original area.

Stress relieving - A process of reducing residual stresses in a metal object by heating the object to a suitable temperature and holding for a sufficient time. This treatment may be applied to relieve stresses induced by casting, quenching, normalizing, machining, cold working, or welding.

Superlattice (superstructure) - A crystal structure that exists in a solid solution when atoms of the different types fall into an orderly arrangement in relation to one another. See ordering.

Tangent modulus - The slope of the stress-strain curve of a metal at any point along the curve in the plastic region. In the elastic region the tangent modulus is equivalent to Young's modulus.

Temper - A condition produced in a metal or alloy by mechanical or thermal treatment and having characteristic structure and mechanical properties.

A given alloy may be in the fully softened or "annealed temper", or it may be cold worked to the "hard temper", or further to "spring temper". Intermediate tempers produced by cold working (rolling or drawing) are called "quarter-hard", "half-hard" and "three-quarters hard", and are determined by the amount of cold reduction and the resulting tensile properties. In addition to the "annealed temper", conditions produced by thermal treatment are the "solution heat treated temper" and the "heat treated and artificially aged temper". Other tempers involve a combination of mechanical and thermal treatments and include that temper produced by cold working after heat treating, and that produced by artificial aging of alloys that are as-cast, as-extruded, as-forged and heat treated and worked.

Tempering - A process of reheating quench-hardened or normalized steel to a temperature below the transformation range, and then cooling at any rate desired.

Tensile strength - The value obtained by dividing the maximum load observed during tensile straining by the specimen cross sectional area before straining. Also called "ultimate strength".

Toughness - Property of absorbing considerable energy before fracture; usually represented by the area under a stress-strain curve, and therefore involving both ductility and strength.

Transformation range or transformation temperature range - The temperature interval within which austenite forms while ferrous alloys are being heated. Also the temperature interval within which austenite disappears while ferrous alloys are being cooled. The two ranges are distinct, sometimes overlapping but never coinciding. The limiting temperatures of the

ranges depend on the composition of the alloy and on the rate of change of temperature, particularly during cooling. See transformation temperature.

Transformation temperature - The temperature at which a change in phase occurs. The term is sometimes used to denote the limiting temperature of a transformation range.

Transition point - The temperature of transformation from one solid crystalline form of a substance to another. More broadly, the point where different phases can exist in equilibrium.

Welding - A process used to join metals by the application of heat. "Fusion welding" which includes "gas, arc and resistance welding", requires that the parent metals be melted. This distinguishes fusion welding from brazing. In "pressure welding" joining is accomplished by the use of heat and pressure without melting. The parts that are being welded are pressed together and heated simultaneously, so that recrystallization occurs across the interface.

Yield point - In mild or medium-carbon steel, the stress at which a marked increase in deformation occurs without increase in load. In other steels and in nonferrous metals this phenomenon is not observed. See yield strength.

Yield strength - The stress at which a material exhibits a specified limiting deviation from proportionality of stress to strain. An offset of 0.2% is used for many metals such as aluminum-base and magnesium-base alloys, while a 0.5% total elongation under load is frequently used for copper alloys.

Young's modulus - The "modulus of elasticity" in tension or compression.

SECTION III

DATA BY MATERIAL

In this section the material property data are tabulated and grouped for each material. The following materials are included:

Alumina

Chromium

Cobalt

Copper (OFHC, beryllium copper, electrolytic, boron deoxidized, chrome-copper)

Copper-Nickel

Forsterite

Gold

Hastelloy B

Inconel

Iron

Kovar

Molybdenum

Monel (403)

Nichrome V

Nickel (Grade A, 202, 220, 225, 330, Duranickel, Low carbon nickel)

Platinum

Rhenium

Stainless Steel

Tantalum

Titanium

Tungsten

Zirconium

Material: Alumina

Chemical Composition: 99% min. Al_2O_3

Trade Designations: High Purity Alumina, 99% Alumina, Alumina

Suppliers: American Lava Corp., Chattanooga, Tenn.

Centralab, Div. of Globe Union Co., Milwaukee, Wisc.

Coors Porcelain Co., Golden, Colo.

Diamonite Products Mfg. Co., Shreve, Ohio

Frenchtown Porcelain Co., Trenton 9, N. J.

Gladding, McBean & Co., Los Angeles 39, Calif.

U. S. Stoneware, Orrville, Ohio

Western Gold & Platinum Works, San Francisco 7, Calif.

Forms Available: Rod, sheet, slab, tube, special shapes

General:

High purity alumina described in this report refers specifically to alpha alumina. Alpha alumina in the polycrystalline state is known commercially as corundum; the single crystal material is sapphire or ruby. Many engineers are fairly well acquainted with the excellent mechanical and electrical properties of sapphire.

Volume resistivity and loss factor of alumina are very good even up to 500°C and above. Mechanical properties are degraded only slightly at elevated temperatures up to within a few hundred degrees of the melting point of 2050°C.

Some of the available commercial literature shows 97% alumina having electrical properties which are superior to the 99% + material. The reason is that the 97% material may be fluxed with silica, titania or some other material which does not appreciably increase rf losses. "High purity alumina", however, may contain up to about one-half percent sodium oxide. This alkali content increases rf losses appreciably.

Special Handling Techniques and Formability:

Parts made of alumina should be fired as nearly as possible in the final form. Once fired, high purity alumina cannot be further machined although it may be cut or ground using diamond wheels, and limited forming is possible with ultrasonic vibrating tools such as the Cavitron.* Pieces which are in the "green" state may be machined or ground as desired, but some shrinkage always occurs on firing and allowance must be made for this. Components with variable wall thickness are difficult to fire with uniform shrinkage. It is usually better to design parts made up in such a fashion that straight rods, cylinders, and flat plates can be assembled into final form. Extreme flatness or parallelism is difficult to obtain in the normal production of ceramic components. It is, therefore, better to design structures so that the metallic members can take up any variation in size of the ceramic portion. Where this cannot be done, several other expedients can be used. For example, the use of isostatic pressing techniques, slip casting, and high pressure molding methods along with machining of the unfired material can improve final tolerances by about an order of magnitude.

*Cavitron Electronic Oscillator Co., 355 W. Newport Blvd., Newport Beach, California

Joining:

Alumina can be metallized in a hydrogen atmosphere using molybdenum-manganese or molybdenum-iron powder surface coatings. It is also amenable to the titanium or zirconium hydride "active metal" metallization using a vacuum of 10^{-5} mm or better. Molten aluminum or chromium will also wet this ceramic under the proper conditions. Thus it is possible to obtain vacuum tight ceramic-metal seals using several different approaches. One of the simplest methods is through the use of a press fit or shrink fit where the ceramic portion is the inner member of a composite cylinder and the metal is the outer member. Since alumina has extremely high compressive strength, it is possible to design a seal of which the metallic portion is under high tension and remains under tension even when the entire structure is heated to 500°C .

For assemblies where vacuum tightness is not necessary, it is usually possible to build structures using only mechanical fastening methods. This is adequate in most cases for the construction of electron guns, cathodes, etc. Brazing is recommended for structures to be subjected to high acceleration or vibration.

Allotropic Changes:

Alumina does not undergo any allotropic changes on heating or cooling, nor is crystal growth a problem at normal tube processing temperatures.

Ease of Outgassing:

Porous alumina parts for internal use in tubes are preferred. Since the material is quite inert, no particular problems are encountered in the handling

ALUMINA

of parts. Normal cleanliness procedures should be adequate. Organic contaminants can be removed by firing in air at 400-600°C if this is necessary. Alumina may also be fired in vacuum or hydrogen if desired. Alumina outgasses readily at temperatures of 1000°C in vacuum.

Typical Applications:

Ceramic parts generally are used for spacers in any tube structure where voltage differences may be encountered between various electrodes. They may also be used as transmission windows for rf energy and to form part of the wall of vacuum envelopes.

Outside of the tube alumina may be used in firing jigs or for assembly jigs, especially where extreme hardness, chemical resistance and wear resistance are considerations. Alumina is also used for insulators, coil forms, condenser shafts, capacitor and resistor cores.

Table 1
ALUMINA (ALPHA) DATA

		<u>Ref.</u>
Density	3.9 gm/cc	71
Lattice Type	Close-packed hexagonal	
Melting Temp.	2040°C	15, p. 28
Impact Resistance	3.0 Charpy inch-pounds	71
Tensile Strength	34,000 psi	71
Compressive Strength	340,000 psi	68
Modulus of Elasticity	40×10^6 psi	68
Specific Heat	0.304 cal/gm°C (20-1000°C)	15, p. 28
Linear Thermal Expansion	7.7×10^{-6} in/in/°C (20-760°C)	
Emissivity Ratio	0.15 at 0.655 μ from 100-1600°C	
Electrical Resistivity	10^{14} to 10^{16} ohm-cm	
Magnetic Susceptibility	-0.23×10^{-6}	
Secondary Electron Emission	max. = 15 at 350V	17
	max. = 4.8 at 1300V	17
Dielectric Constant	10.9 at 1 MC and 21°C	68
	8.8 at 8500 MC and 21°C	68
Power Factor	.0003 at 1 MC and 21°C	68
	.0002 at 8500 MC and 21°C	68
Loss Factor	.0033 at 1 MC and 21°C	68
	.0018 at 8500 MC and 21°C	68
JAN-I-10 Electrical Grade	L-6	68
Dielectric Strength	220 V/mil	71

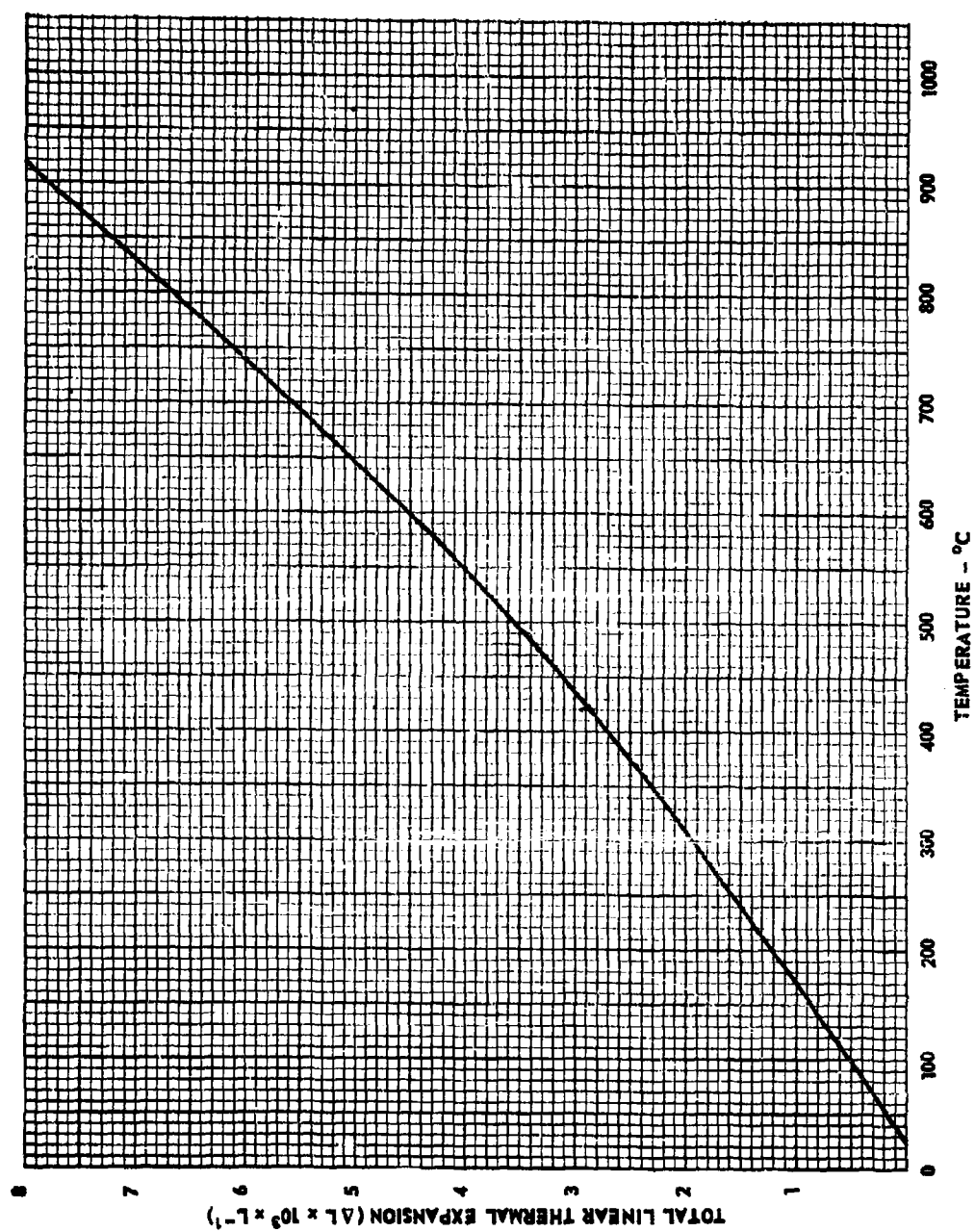


Fig. 1 — Linear Thermal Expansion of Alumina

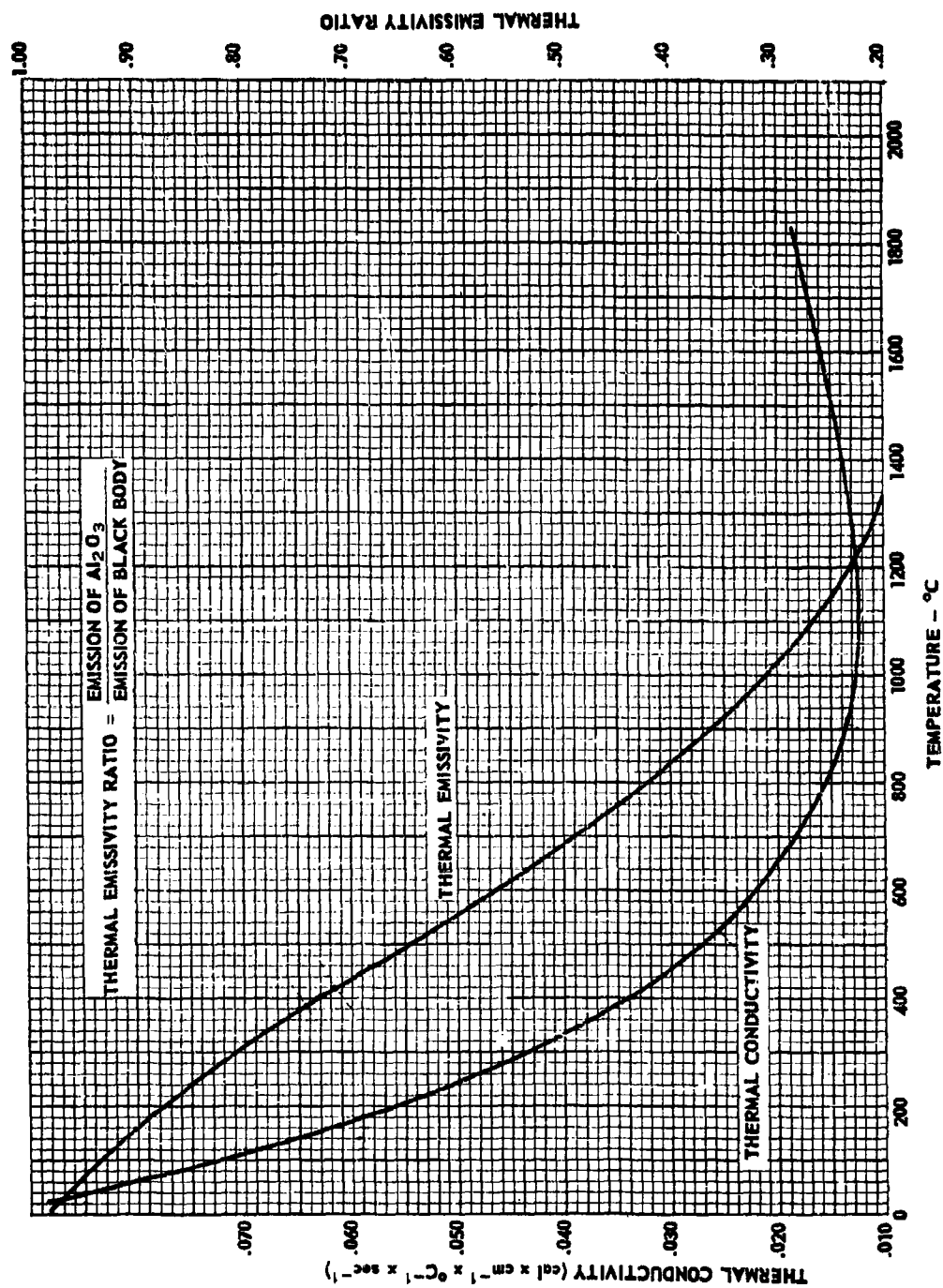


Fig. 2 — Thermal Emissivity and Conductivity of Alumina

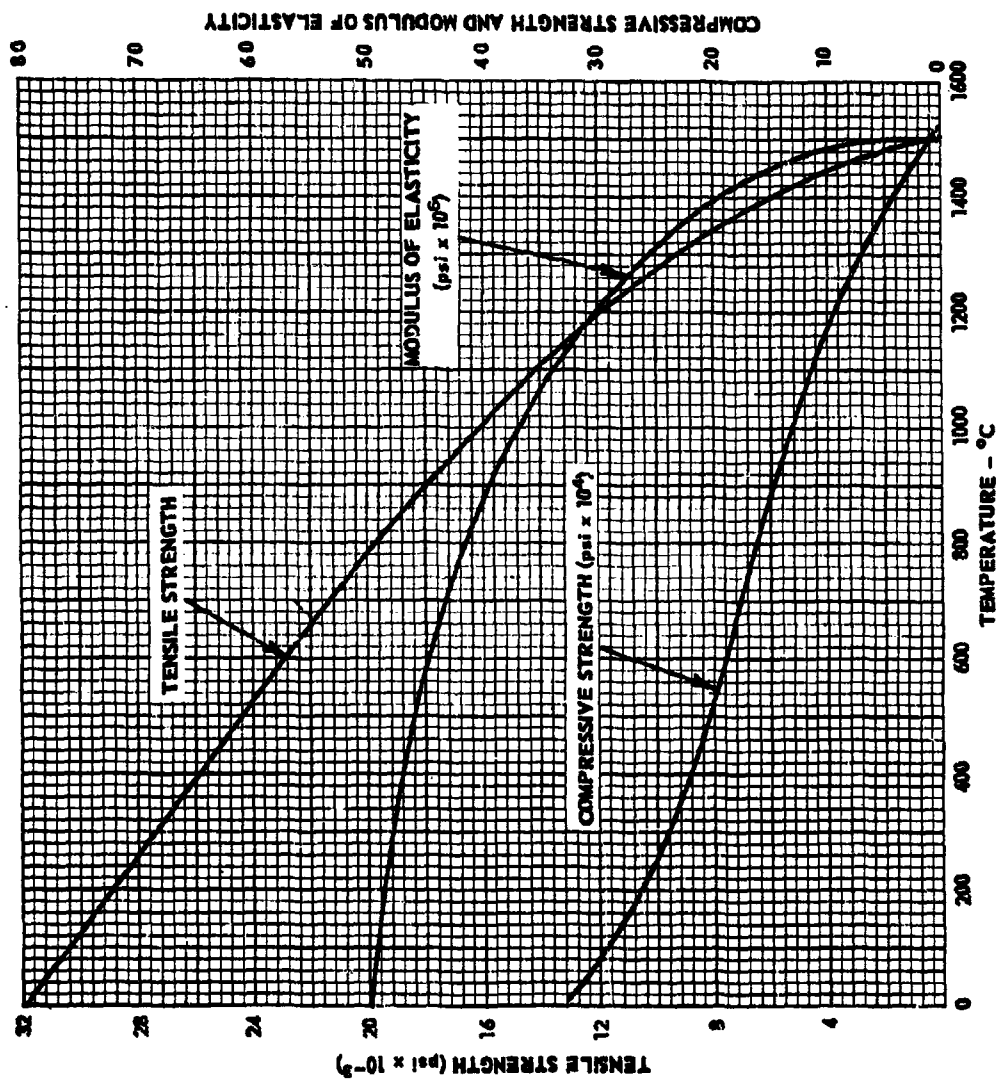


Fig. 3 — Mechanical Properties of Alumina

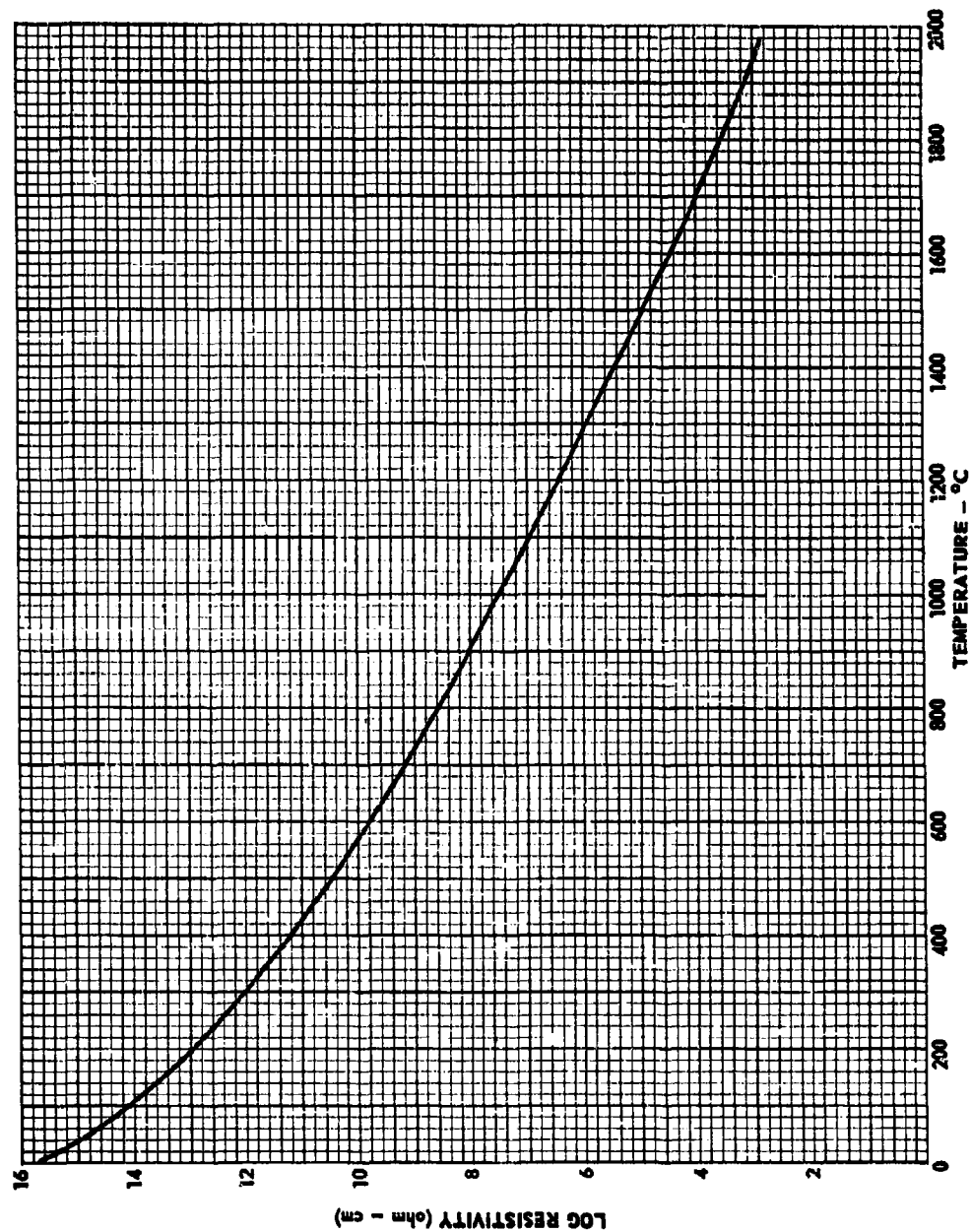


Fig. 4 -- Electrical Resistivity of Alumina

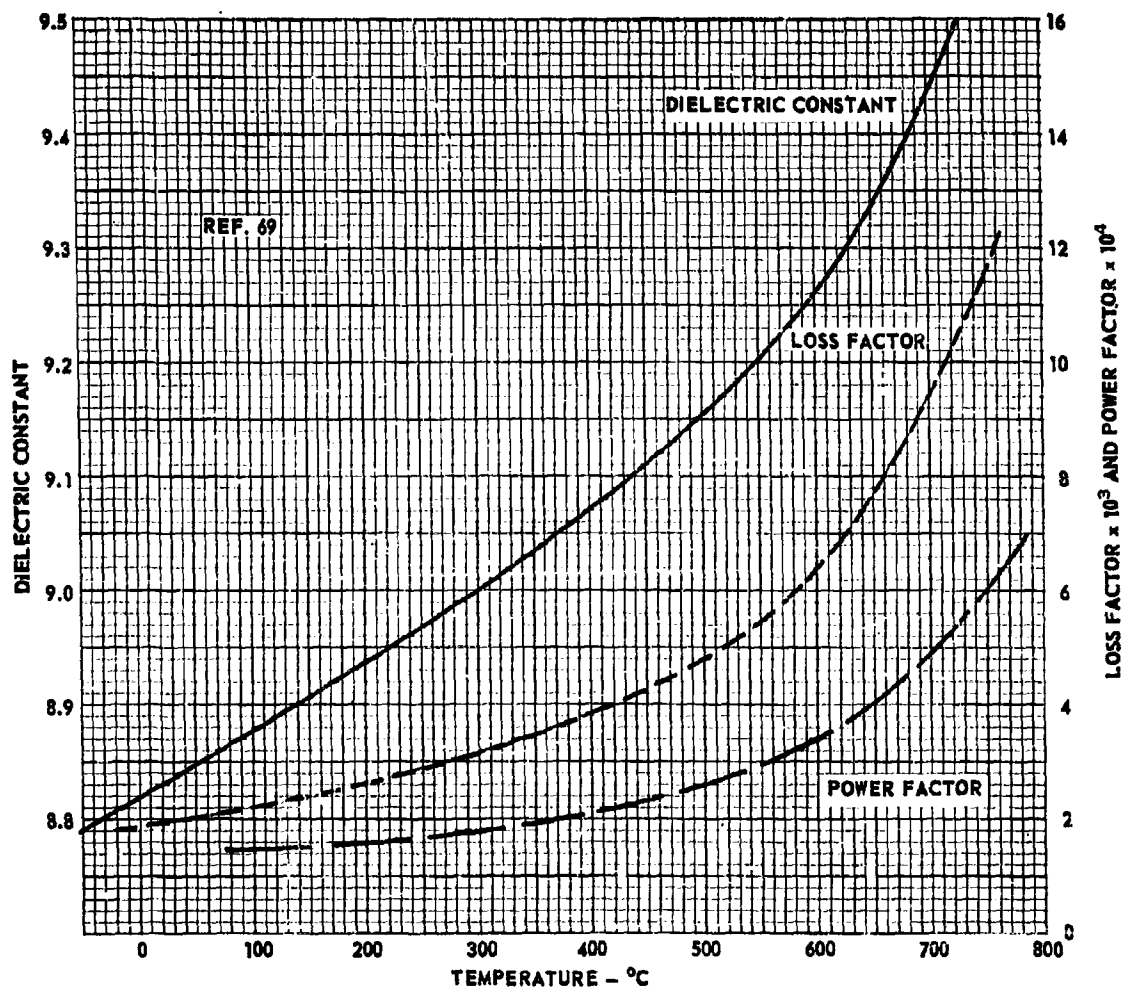


Fig. 5 — Power Factor, Dielectric Constant and Loss Factor at 8500 MC for Alumina

Material: Chromium

Chemical Composition: 99.7% Chromium (min)

Trade Designation: Chromium

Suppliers: Belmont Smelting & Refining Works, Inc., 330 Belmont Ave.,
Brooklyn 7, N. Y.

Bram Metallurgical-Chemical Co., 820 65th Ave.,
Philadelphia 26, Pennsylvania

Electrolizing Sales, Inc., 1406 E. 15th St., Los Angeles 21,
California

Kawecki Chemical Co., 220 E. 42nd St., New York 17, N. Y.

Metal & Thermit Corp., Rahway, N. J.

Van der Horst Corp., Olean, N. Y.

General:

Chromium, in spite of its wide-spread use in alloys and as electroplating material, has only recently become available in the massive form. There are several reasons for this. Chromium is rather difficult to produce in a highly purified state, and unless it is extremely pure, fabrication is almost impossible.

Chromium is a member of Group VI A in the periodical table, along with molybdenum and tungsten, and would be expected to show some of the good high temperature properties associated with these metals. It is, however, somewhat disappointing in this respect so far as electronic work is concerned. Chromium plating and surface alloying as in the "chromizing" process are, however, widely used and have still greater

potential for corrosion resistant exterior surfaces for high temperature tubes.

Special Handling Techniques and Formability:

Chromium seems to be more reactive than tungsten or molybdenum in that it readily absorbs oxygen, nitrogen, hydrogen, carbon and sulfur. Any of these elements may cause excessive hardening, embrittlement, and formation of a structure which is impossible to machine or even bend. Besides this, the vapor pressure of chromium is higher by several orders of magnitude than that of molybdenum. Vapor pressure tests made on a chromium alloy (Nichrome V) indicate that its alloys with nickel evaporate much more rapidly than would be predicted on the basis of Raoult's Law.

There is evidence to indicate that .002% nitrogen or .02% oxygen has a measurable effect on the ductile-brittle transformation temperature. In forging or rolling at 800°C or higher, chromium must be protected by a jacket or sheath of steel in order to inhibit atmospheric effects.

Chromium resembles tungsten somewhat in its response to cold-work; that is, continued working leads to smaller grain size and to higher ductility or lower brittle temperature. If worked at 350 - 400°C annealing is unnecessary. Cold-working produces some hardening and strengthening.

Chromium seems to be very sensitive to notch effects. All parts which have been heated in air for annealing or forming should be etched or abraded to remove the brittle surface layer caused by pick-up of nitrogen or oxygen. Bending and forming operations are greatly simplified if this surface layer has been removed. Electroplated chromium recrystallizes at about 400°C.

According to Dushman⁴, the solubility of hydrogen in chromium is between that of cobalt and copper.

Hot-work temperature is given as 1250°C. Sintering temperature is 1300°C. The material should be sintered under high vacuum until free of gases. Parts may then be heated to 1600-1700°C in an inert atmosphere, such as argon, for further consolidation.

Joining:

Silver brazing may be used for joining chromium to itself or to other metals. Close control over the dryness of the hydrogen atmosphere must be exercised however, since a surface oxide could form which will not be wet by the brazing filler metal. Spot-welding is also feasible.

Allotropic Changes:

Either the cubic or hexagonal form may be found at room temperature. The transformation temperature from hexagonal to cubic is reported by Vaughan¹⁵ to be 26°C.

Ease of Outgassing:

Hydrogen can be removed readily at 500-600°C in vacuum. Chromium oxides, however, are very stable and should be removed by chemical or mechanical methods before assembly into a vacuum-tube structure if clean metal surfaces are necessary.

Applications:

The bulk of the chromium used in this country goes into ferrous alloys such as the stainless steels, which are useful for their corrosion

CHROMIUM

resistance and lustrous finish. Many high-temperature alloys also contain chromium.

Chromium plated surfaces are sometimes used in vacuum tubes in order to increase thermal emission or externally, to improve corrosion resistance. Chromium alloys are frequently used for resistive elements, anodes, grids, support structures, etc.

CHROMIUM

Table 2
CHROMIUM DATA

		<u>Ref.</u>
Density	7.20 gm/cc	14
Lattice Type	Body-centered cubic	15
Melting Temperature	1890 \pm 10°C	14
Modulus of Elasticity	36 x 10 ⁶ Psi	7
Thermal Conductivity	.16 cal.cm/cm ² .sec°C	7
Specific Heat	.11 cal/gm°C	7
Linear Thermal Expansion	6.5 x 10 ⁻⁶ in/in/°C (0 - 500°C)	7
Curie Point	Nonmagnetic	
Electron Work Function	4.60 eV	50
Richardson Constant 'A'	48	50
Temp. for 10 ⁻⁵ mm Vapor Pressure	1062°C	81

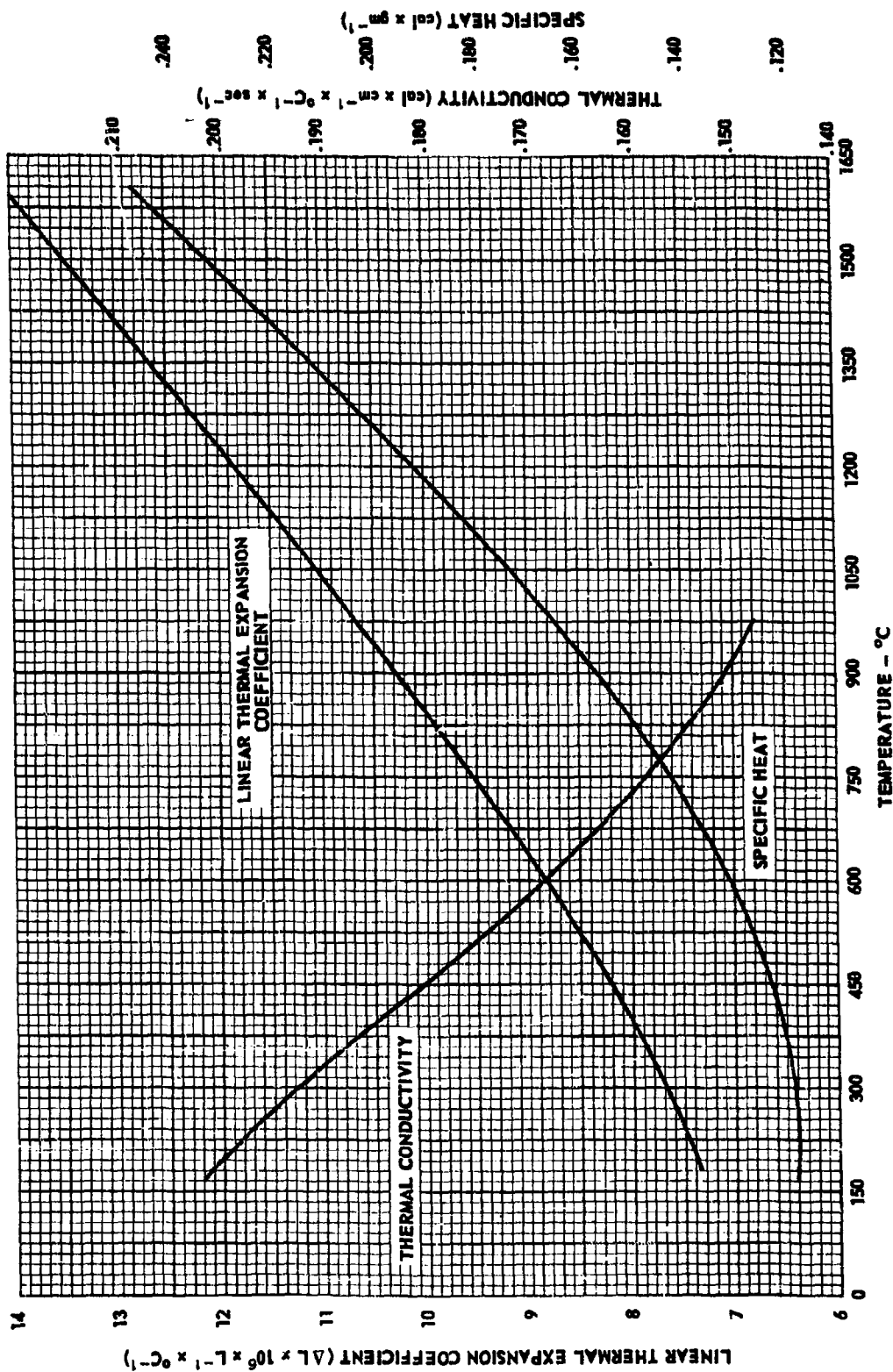


Fig. 6 — Thermal Conductivity, Specific Heat and Coefficient of Thermal Expansion for Chromium

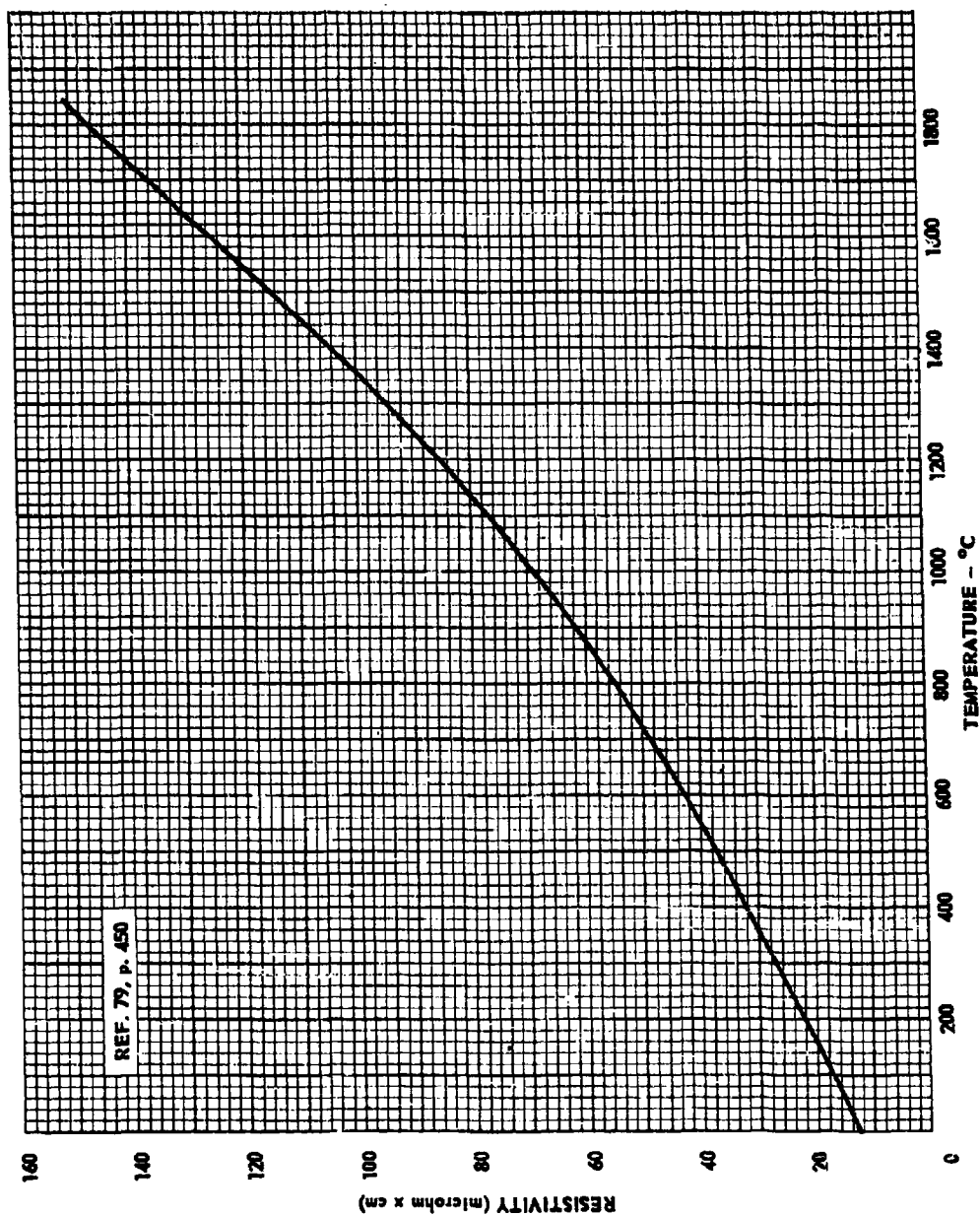


Fig. 7 — Electrical Resistivity of Chromium

COBALT

Material: Cobalt

Chemical Composition:	Cobalt	- 98.6%	Manganese	- 0.12%
	Nickel	- 0.7%	Copper	- 0.03%
	Iron	- 0.37%	Sulfur	- 0.04% max.
	Silicon	- 0.12%		

Trade Designation: Cobalt

Suppliers: International Nickel Co., 67 Wall St., N. Y. 5, N. Y.

Deloro Smelting & Refining Co., Ltd., Deloro, Ontario

National Lead Co., Fredericktown, Missouri

Pyrites Co., Wilmington, Delaware

Forms Available: Powder, bar, rod, billets

General:

Cobalt is in many respects similar to iron and nickel in its chemical reactions, and along with them forms the first triad in the periodic table. It is ferromagnetic, with a permeability about two-thirds that of iron, and has the highest Curie point of any element. Cobalt is very rarely used in elementary form. It may be necessary to consider cobalt, however, for high temperature applications in which it is necessary to work with magnetic fields since cobalt retains magnetic characteristics up to 1100°C.

Special Handling Techniques and Formability:

Pure cobalt is quite sensitive to the presence of traces of other elements; physical properties can vary over a wide range in the presence of 1% or less of impurities such as oxygen, carbon, sulfur or silicon.

The density of beta cobalt is given as 8.94 gms/cc while that of alpha cobalt is 8.90 gms/cc, indicating a volume change of about 0.3% as the metal passes through the transformation temperature range.

The thermal expansion of pure beta cobalt varies between 12.6×10^{-6} and 16.1×10^{-6} depending upon the crystal orientation. For polycrystalline material the intermediate value of 13.8×10^{-6} at room temperature is accepted. It is possible that thin films or wire may show non-uniform expansion in different directions.

Some of the physical and mechanical properties of cobalt in massive form have not yet been determined. However, since cobalt is rarely used alone, the machining characteristics, tensile strength, yield strength, etc., are of less value than similar characteristics of metals like iron and nickel. The major difference which separates cobalt from iron and nickel is its hexagonal crystal structure.

Joining:

The welding and brazing of pure cobalt are not reported, but judging from its position in the periodic table it should be similar to iron or nickel in behavior.

COBALT

Allotropic Changes:

Cobalt exists in two allotropic forms. Below 400°C the hexagonal close-packed structure (beta form) is stable, but above this temperature the alpha face-centered cubic form exists. The transformation is quite sluggish and most samples at room temperature contain both alpha and beta cobalt. There have been reports of a second transformation near the Curie point but this has not yet been substantiated.

Applications:

Most of the cobalt produced today goes into the manufacture of special alloys which show outstanding high temperature characteristics on the one hand and unique magnetic applications on the other. For example, Alnico V contains 24% cobalt and many high speed steels contain between 10 and 40% cobalt. The metal is also used as a binder for tungsten carbide in the production of carbide cutting tools. Some cobalt alloys such as Kovar are used in the electronic industry for sealing to glass or ceramics.

Table 3
COBALT DATA

		<u>Ref.</u>
Density	8.92 gm/cc	5
Lattice type	Close-packed hexagonal and Face-centered cubic	5
Melting Temperature	1493°C	5
Transformation Temp. (β to α)	417 \pm 7°C	5
Tensile Strength	100,000 Psi (wire)	5
Yield Strength	42,000 Psi	5
Modulus of Elasticity	30 x 10 ⁶ Psi	5
Maximum Elongation	2%	7
Thermal Conductivity	.17 cal/cm/cm ² .sec.°C	5
Specific Heat	.1056 cal/g/°C	5
Linear Thermal Expansion Coefficient	13.8 x 10 ⁻⁶ in/in/°C (20 - 600°C)	5
Electrical Resistivity	6.24 x 10 ⁻⁶ ohm-cm (20°C)	7
Temp. Coefficient of Resistivity	60.4 x 10 ⁻⁴ /°C	7
Curie Point	1121°C	5
Electron Work Function	4.41 eV	50
Richardson Constant 'A'	41	50
Temperature for 10 ⁻⁵ mm Hg Vapor Pressure	1162°C	81

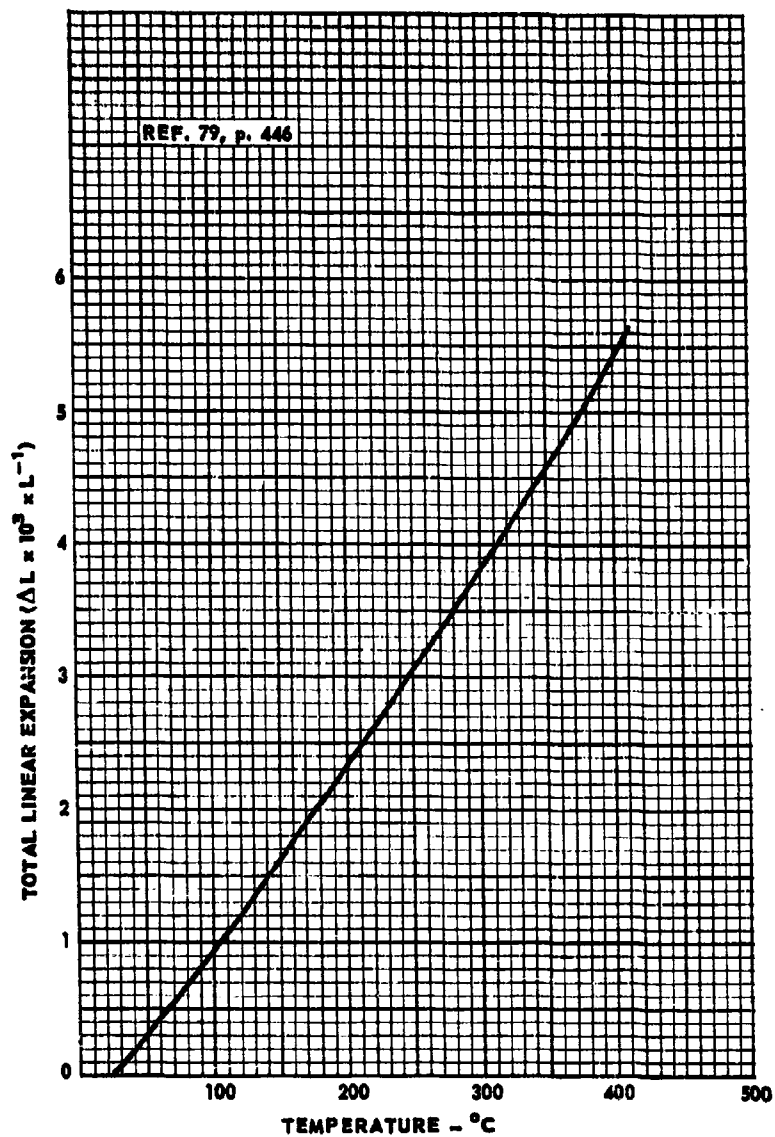


Fig. 8 — Linear Thermal Expansion of Cobalt

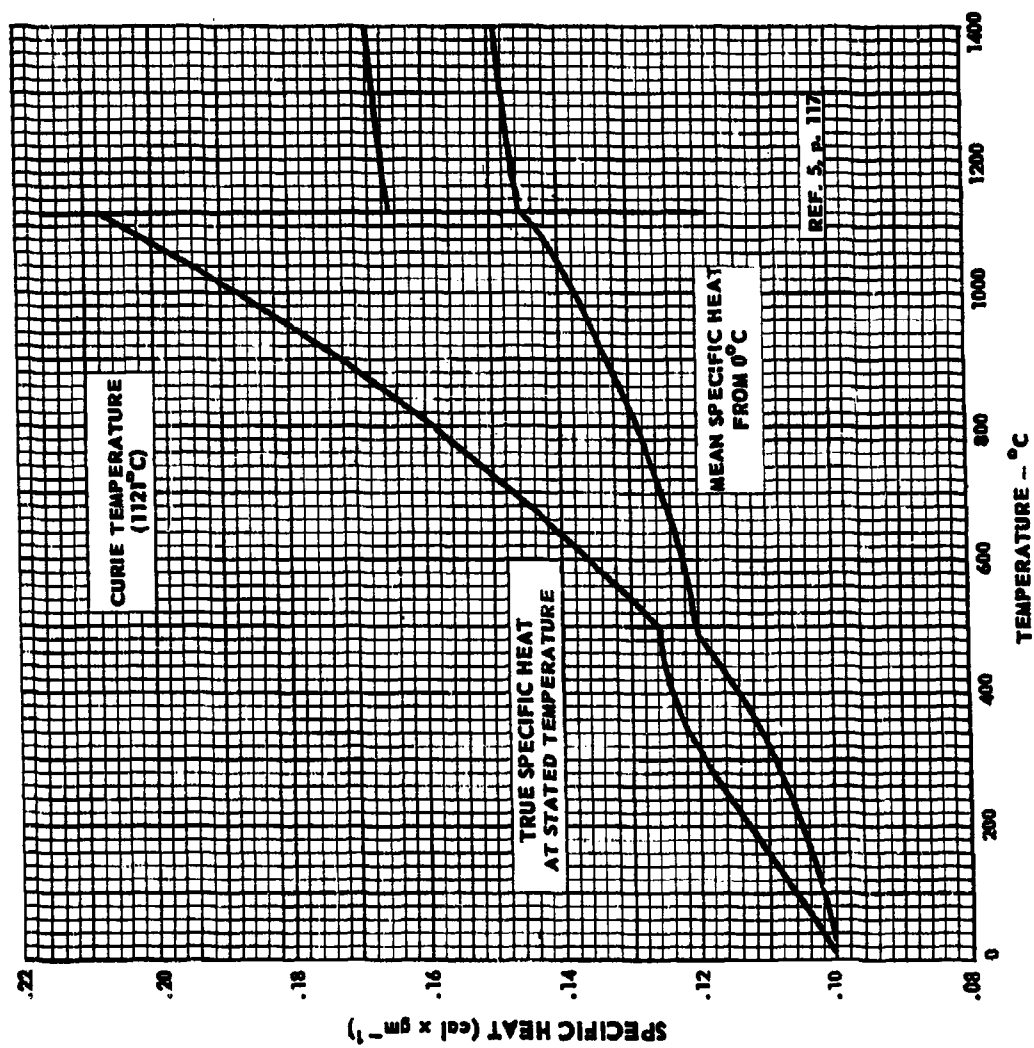


Fig. 9 — Specific Heat of Cobalt

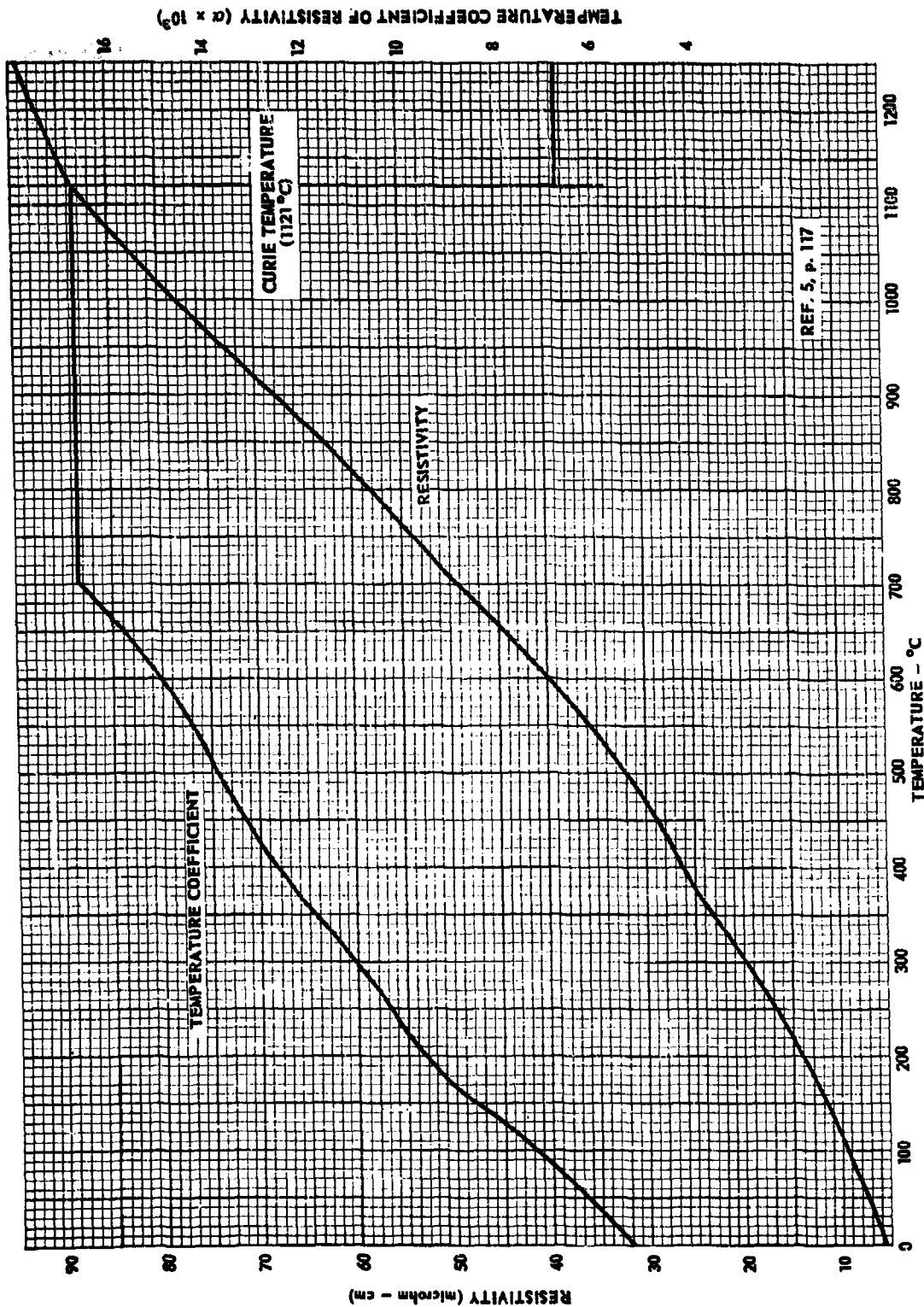


Fig. 10 — Electrical Resistivity and Temperature Coefficient of Resistance for Cobalt

COPPER

Material: Copper

Chemical Composition (OFHC):¹

Copper+Silver	- 99.96 min.
Phosphorus	- 0.0003 max.
Mercury	- 0.0001 max.
Sulfur	- 0.004 max.
Zinc	- 0.007 max.
Lead	- 0.0001 max.

Trade Designations: Oxygen-free copper and OFHC copper

Supplier: American Metal Co., Ltd., 61 Broadway, New York 6, N. Y.

Forms Available: Wire, bar, rod, sheet, strip, foil, tube

General:

This material description is concerned almost exclusively with high purity oxygen-free copper (OFHC). There are a great number of copper alloys, however, which are useful in electronic work. A list of these alloys, with a few brief comments, is included:

Electrolytic tough-pitch copper -

Good for exterior parts such as radiator fins, plugs, tubing, etc. - should not be fired in hydrogen nor used inside the tube envelope. Contains 99.9% copper+silver and about .04% oxygen.

1. T. M. Reg. American Metal Co., Ltd., 61 Broadway, New York 6, N. Y.

COPPER

$\frac{1}{2}$ % Beryllium copper -

Good machinability after heat treatment - high thermal and electrical conductivity - excellent formability in soft condition - high strength and hardness after heat treatment. Contains 0.4 to 0.7% beryllium plus about $2\frac{1}{2}$ % cobalt. May be hydrogen fired and may be used inside the tube.

2% Beryllium copper -

Similar to $\frac{1}{2}$ % beryllium copper but harder after heat treatment. Easily formed while soft - spring temper when hard - may be hydrogen fired and used inside the vacuum. Contains about 2% beryllium.

Chemically deoxidized copper -

Easy to machine - higher strength and hardness than OFHC. Should not be used inside the tube envelope nor as brazing compound with nickel alloys. Contains 99.9% copper+silver and about 0.05% phosphorus.

Copper-silver alloy made with OFHC copper -

Higher softening temperature and higher strength than pure copper. Thermal and electrical conductivity high. Contains over 99.9% copper with about .06% silver. Can be used for tube parts inside or outside the vacuum. Can be hydrogen fired.

Boron deoxidized copper -

Easy to machine - used for anodes, exhaust tubes, grids, side rods and brazing alloys - may be hydrogen fired and used in tubes - contains over 99% copper - about .02% boron. Conductivity about 96% IACS.

1% Chrome copper -

Good machinability - used for grids and side rods - good strength - high electrical and thermal conductivity - contains about 1% chromium,

Metallic copper for the construction of microwave devices is usually of the OFHC type with oxygen contents held to less than .0007% during the melting and casting processes. No additional elements are added. This is in contrast to deoxidized coppers containing active scavengers which react with and remove oxygen from solution.

Copper is perhaps the easiest material to form of any listed in this manual, however, it is not necessarily easy to machine. Cavities for magnetrons and klystrons are made almost universally of high purity copper; they can be hot-hobbed to close tolerances with fine finishes on a production scale.

There are several serious limitations to the use of copper in devices which will be operated at 500°C. The first of these limitations is vapor pressure; a pressure of about 10^{-8} mm at 700°C is accepted for copper. Since tubes are expected to be outgassed at temperatures higher than their service temperatures, it is obvious that some copper may evaporate while on exhaust. This may lead to unwanted conductive surfaces on insulating supports.

Other disadvantages are low oxidation resistance and mechanical weakness.

Copper components begin to oxidize at about 400°C and oxygen is soluble in the copper. Also, because of its low annealing temperature, pure copper

will be in the "dead soft" condition after processing; thin walls will be too weak to withstand one atmosphere pressure without deformation.

Special Handling Techniques and Formability:

High purity copper is rather difficult to machine because it is so very ductile. Tapping is not generally recommended as a fastening procedure; other forms of mechanical fastening are sometime used but brazing is considered best. If copper is supported by a rigid material and protected from oxidation, then it may be used for high reliability (but not necessarily long-life) tubes at 500°C. The metal responds to hobbing, bending, coining, flaring, stamping and punching.

Joining:

Besides its ease of forming, copper may be joined to itself or to other metals by soldering, brazing, welding or riveting. Spot-welding is difficult because of the high electrical and thermal conductivity.

The softness and plasticity of copper at room temperature may be utilized in making glass seals where the differential coefficient of expansion may be quite large but strains are minimized by the low yield strength of the metal. Copper discs may be easily sealed into glass tubing or glass discs into copper tubing provided the thickness of the copper is held to about 15 mils or less, depending on the geometry and type of glass used.

Allotropic Changes:

There are no allotropic changes on heating or cooling. OFHC copper may be hydrogen fired at about 900°C for up to one hour without excessive impairment of mechanical properties.

COPPER

Ease of Outgassing:

After hydrogen firing, parts may be outgassed in vacuum readily at about 650°C in three to ten minutes depending upon wall thickness.

Applications:

Applications of OFHC copper are numerous in the microwave industry in building magnetrons, Klystrons and traveling-wave tubes and in individual components for the construction of these devices. Vanes, anodes, guard rings and collectors are all frequently made of this material.

COPPER

Table 4
OFHC COPPER DATA

		<u>Ref.</u>
Density	8.96 g/cc	7
Lattice Type	Face-centered cubic	7
Melting Temperature	1083°C	7
Tensile Strength	28,000 psi (room temperature)	7
Yield Strength	2,000 psi	7
Modulus of Elasticity	16 x 10 ⁶ psi	15
Maximum Elongation	60%	7
Thermal Conductivity	.94 cal.cm/cm ² sec.°C	7
Specific Heat	.092 cal/gm°C	7
Linear Thermal Expansion	17.7 x 10 ⁻⁶ in/in/°C	15, p. 905
Electrical Resistivity	1.67 x 10 ⁻⁶ ohm cm	7
Curie Point	Nonmagnetic	
Magnetic Susceptibility	-.086 x 10 ⁻⁶	15
Electron Work Function	4.38 eV	50
Richardson Constant 'A'	65	50
Temp. for 10 ⁻⁵ mm Vapor Pressure	942°C	81

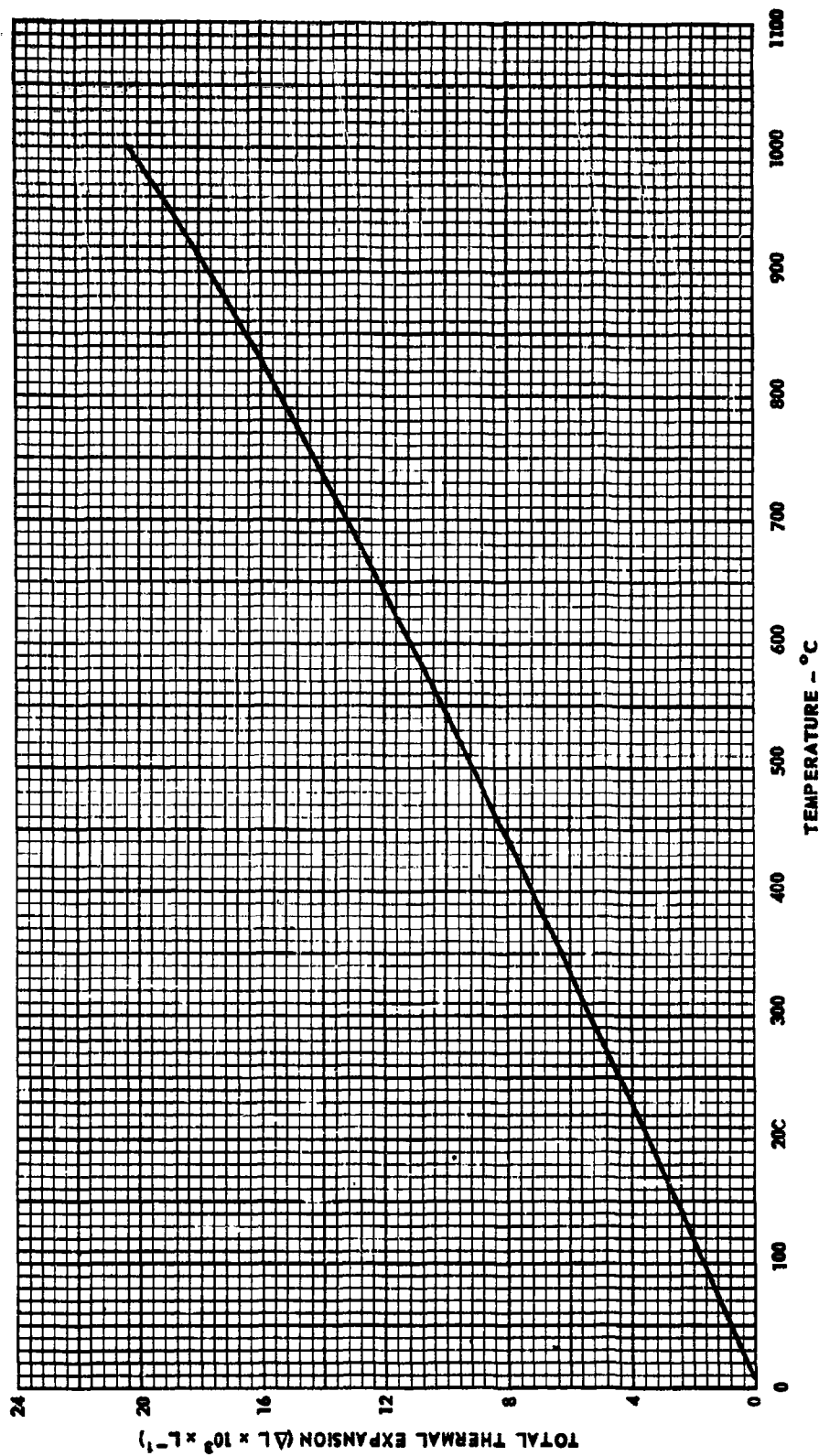


Fig. 11 — Linear Thermal Expansion of Copper

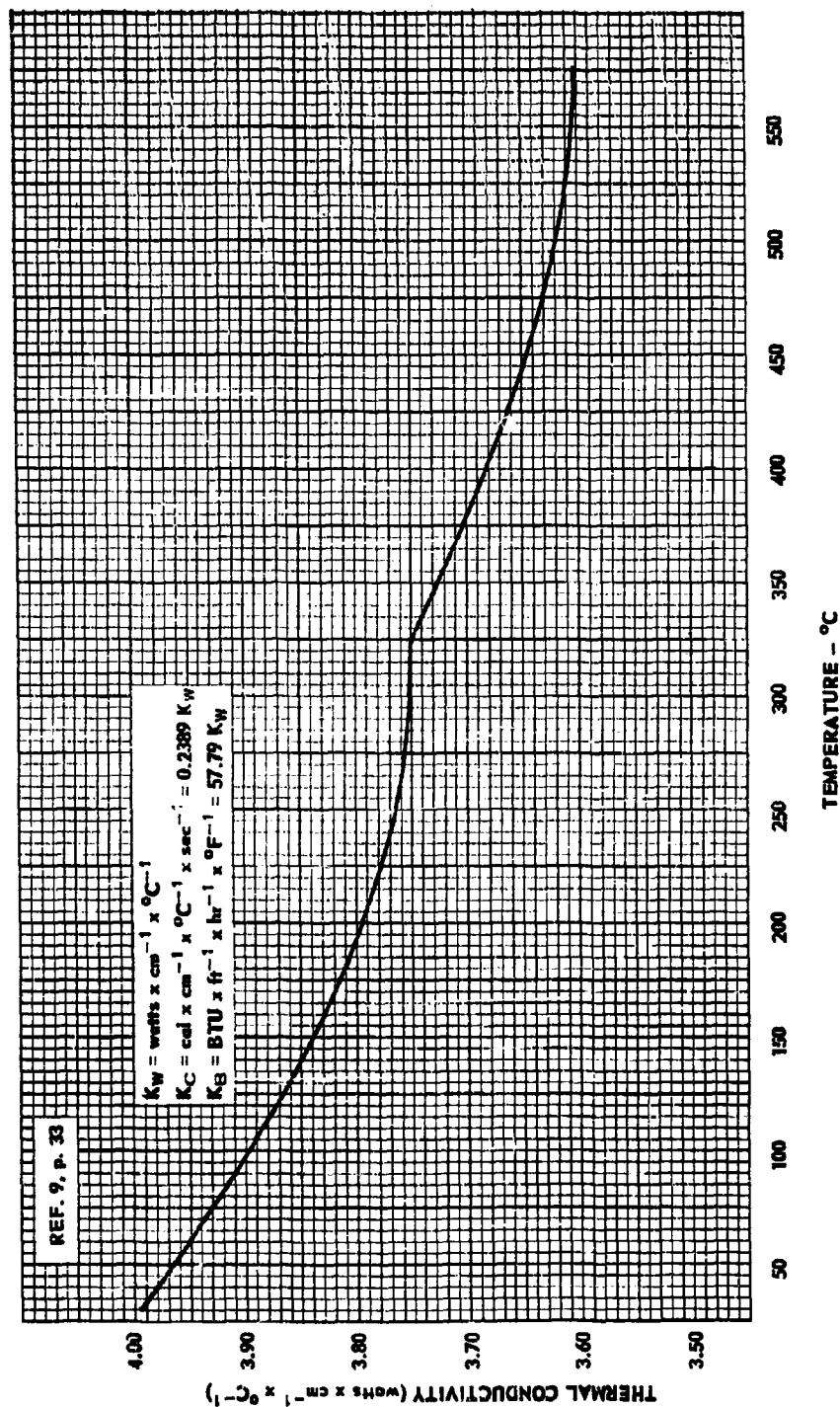


Fig. 12 — Thermal Conductivity of Copper

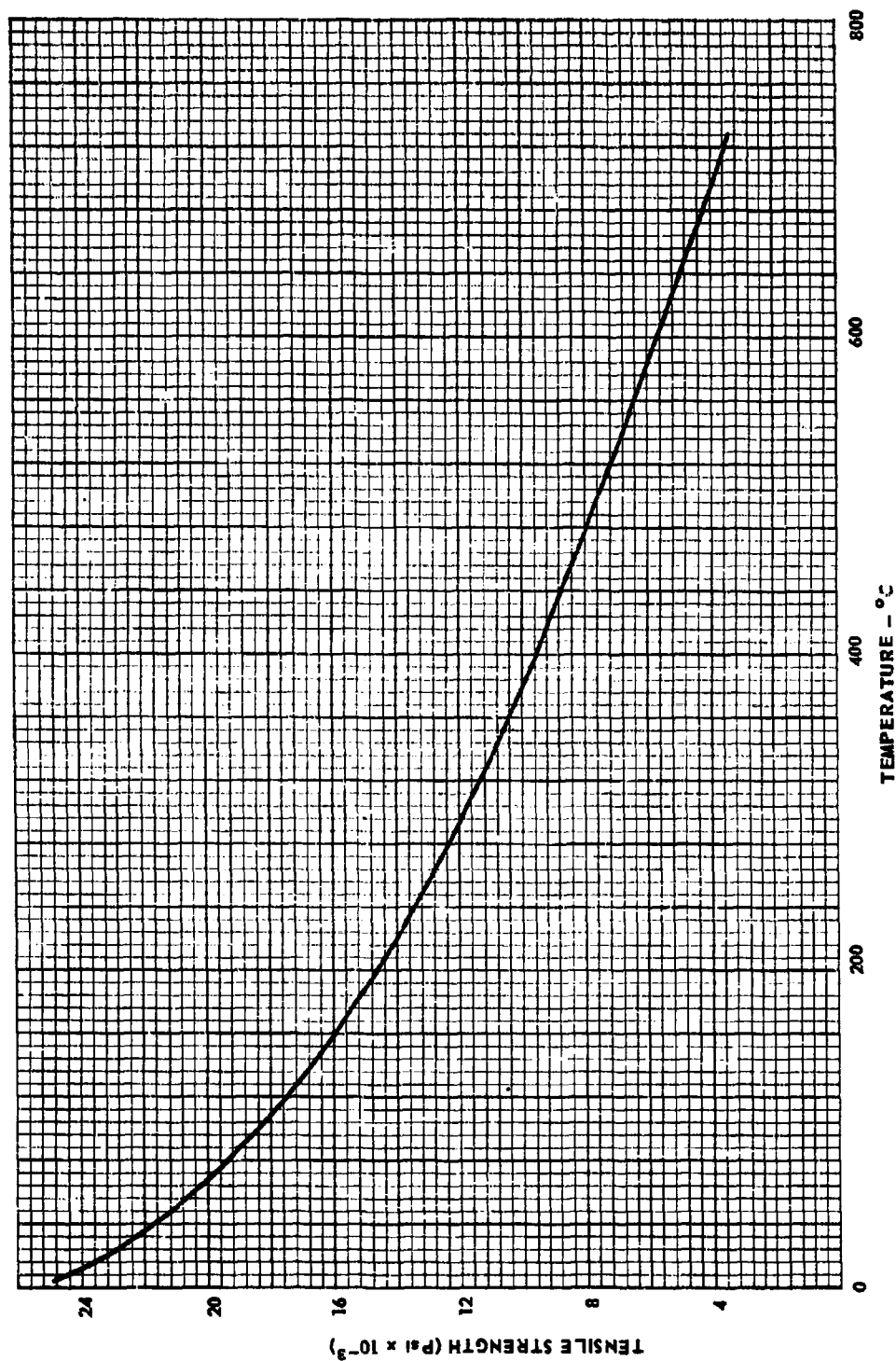


Fig. 13 — Tensile Strength of Copper

COPPER-NICKEL

Material: Copper-Nickel

Chemical Composition:

Nickel	- 29-33%
Lead	- 0.05 max.
Manganese	- 1.00 max.
Copper	- remainder
Tellurium	- 0.60 max.
Zinc	- 0.10 max.
Tin	- 1.5 max.

Trade Names and Numbers: Cupro - Nickel 30%
Revere Alloy #510

Suppliers: American Brass Co., Waterbury, Conn.
Chase Brass & Copper Co., Inc., Waterbury 20, Conn.
Revere Copper & Brass Inc., 230 Park Ave., New York 17, N. Y.

Forms Available: Sheet, strip, rod, tube, wire

General:

Electronic grade 70-30 copper-nickel alloy is very useful for both prototype and production work in the microwave tube field. The machinability is reasonable (about 20% of free-cutting brass); forming operations are not difficult and the material may be brazed, spot-welded or soldered to itself or to other metals. It is non-magnetic at all temperatures, reasonably strong and rigid, free from outgassing or vapor pressure problems and resistant to atmospheric and salt water corrosion. For vacuum tube applications

perhaps the most serious problem is in obtaining material of sufficient purity for use in a vacuum. For example, many regular commercial grades of copper-nickel alloy permit up to 1% zinc, plus lead, manganese and tin. Vapor pressures of all of these elements are too high to maintain a good vacuum if operated at temperatures of 400 to 500°C, and as a result these materials may evaporate conductive films to internal tube surfaces.

Special Handling Techniques and Formability:

Copper-nickel alloys may be hot-rolled or extruded without difficulty but rather close control of pressure and temperature is required in order to achieve consistent results.

Full annealing takes place at 650° to 870°C within 10 to 30 minutes.

In machining, (using high speed steel cutters) a surface speed of 75 to 150 feet per minute is recommended. Roughing feeds usually vary between .015" and .040"; finishing feeds range from .005" to .020".

Joining:

Copper-nickel may be resistance welded (spot-welded) to itself or to nickel, tungsten, molybdenum, Nichrome* or to other resistive metals. Surfaces should be thoroughly cleaned before welding.

It may also be brazed or soldered to a variety of other metals as well as some metallized ceramics. Mechanical fasteners may also be used, such as bolts, rivets, or tabs.

*T. M. Reg. Driver Harris Co.

COPPER-NICKEL

Heat treating or brazing operations in an atmosphere containing sulfurous gases should be avoided. Also to be avoided is brazing with phosphorous bearing filler metals. Embrittlement of the alloy is likely if these precautions are not observed. Hydrogen embrittlement does not seem to be a problem.

Allotropic Changes:

No changes in crystal form are reported during working or annealing. Grain growth is not excessive.

Ease of Outgassing:

Copper-nickel outgasses effectively during bakeout at 450°C after first firing at 950° - 1000°C in dry hydrogen for thirty minutes. It may also be outgassed in vacuum at 950° - 1000°C for one - ten minutes depending on thickness.

Applications:

Copper-nickel alloys are used both for interior and exterior structures in microwave tubes. Typical uses include drift tubes, anodes, jigs and fasteners.

COPPER-NICKEL

Table 5
70-30 COPPER-NICKEL DATA

		<u>Ref.</u>
Density	8.94 gm/cc	15, p. 925
Lattice Type	Face-centered cubic	
Melting Temperature	1170 - 1240°C	15, p. 925
Annealing Temperature	650 - 810°C	15, p. 925
Hot-Working Temperature	925 - 1025°C	15, p. 925
Cold-Working Temperature	Room Temperature	2, p. 7-32
Tensile Strength	55,000 Psi	2, p. 7-32
Yield Strength	20,000 Psi	2, p. 7-32
Modulus of Elasticity	22 x 10 ⁶ Psi	2, p. 7-32
Maximum Elongation	46.5%	7, p. 731
Thermal Conductivity	0.07 cal./cm ² sec.°C	15, p. 925
Specific Heat	0.09 cal./gm°C	15, p. 925
Linear Thermal Expansion	16.2 x 10 ⁻⁶ in/in/°C (20 - 300°C)	15, p. 925
Electrical Conductivity	4.75% I.A.C.S.	7, p. 643
Curie Point	Nonmagnetic	
Temp. for 10 ⁻⁵ mm Vapor Pressure	960°C	73

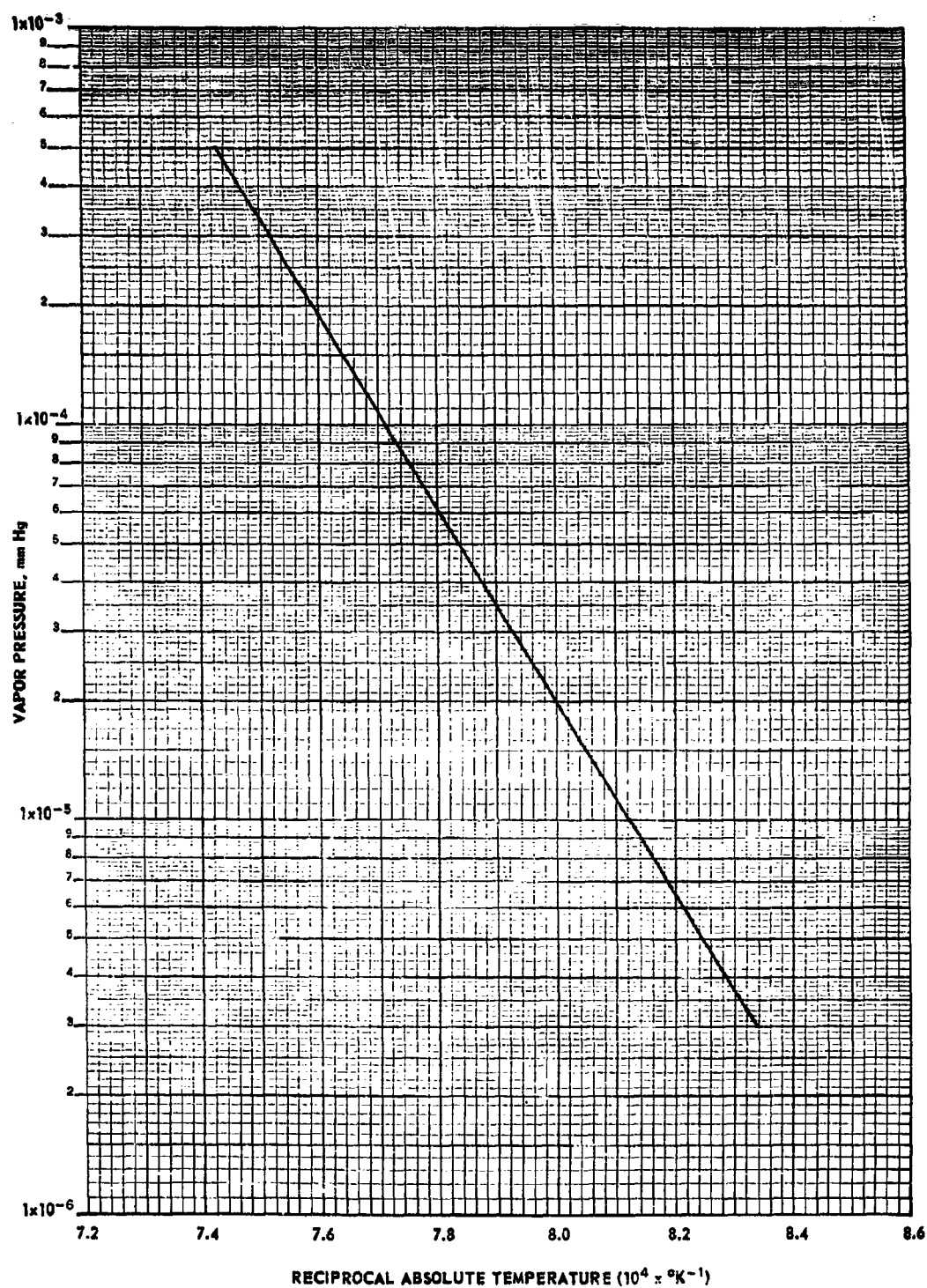


Fig. 14 — Vapor Pressure of 70-30 Copper-Nickel Alloy

Material: Forsterite

Chemical Composition: $2\text{MgO} \cdot \text{SiO}_2$

Trade Designations: Forsterite, Alsimag 243*, Stupakoff No. 2500

Suppliers: American Lava Corp., Chattanooga 5, Tenn.

Stupakoff Division of Carborundum Co., Latrobe, Penna.

Forms Available: Slabs, rods, cylinders, molded shapes, tube

General:

Forsterite is related to steatite ($\text{MgO} \cdot \text{SiO}_2$) but has higher magnesia content. The excess magnesia lowers the electrical loss factor but increases thermal expansion. Thus, forsterite is less resistant to thermal shock than steatite. It has very low dielectric losses and is less permeable than glass to the diffusion of helium.

Special Handling Techniques and Formability:

As is true of fired ceramics generally, machining is difficult or impossible. After firing, forsterite compositions may be formed by diamond wheel or ultrasonic grinding machines. Forsterite may be fired in hydrogen or in vacuum without breakdown or reduction to free metal.

Commercial forsterite may contain small amounts of MnO_2 , Fe_2O_3 , TiO_2 , Al_2O_3 , and smaller quantities of Na_2O or K_2O . In general, these will be derived from the fluxes or clay added in the course of fabrication.

*T.M. Reg. American Lava Corp.

FORSTERITE

Forsterite has relatively high firing shrinkage (up to 20%) which limits the precision of fired parts. It is vacuum tight after firing.

Joining:

The thermal expansion curve of forsterite is sufficiently similar to that of 16% chromium-iron to permit reasonably good ceramic-to-metal seals to be made. Molybdenum and molybdenum-manganese metallizing techniques may be used. Titanium or zirconium hydride will also yield good seals if properly applied and fired.

Allotropic Changes:

There are no allotropic changes on heating or cooling.

Base of Outgassing:

The material outgasses during tube bake-out processing at 450°C. It can be heated to 1200°C without measurable vaporization of ceramic. A tube with forsterite insulators may, however, be difficult to process at very high temperatures because of internal stresses and seal stresses resulting from the high coefficient of expansion of forsterite.

Applications:

Forsterite is used for insulators, supports and envelopes. It is also used for vacuum-tight rf windows.

FORSTERITE

Table 6
FORSTERITE DATA

		<u>Ref.</u>
Density	2.8 g/cc	2, p. 42-17
Softening Temp.	1440°C	2, p. 42-17
Max. Continuous Service Temp.	1100°C	2, p. 42-17
Thermal Expansion Coeff.	20-100°C 9.0×10^{-6} 20-700°C 10.0×10^{-6}	2, p. 42-17 2, p. 42-17
Thermal Conductivity	0.008 cal/cm/°C/sec.	2, p. 42-17
Flexural Strength	18,000-20,000 psi	17, p. 38
Tensile Strength	10,000 psi	2, p. 42-17
Compressive Strength	85,000 psi	2, p. 42-17
Dielectric Strength	240 volts/mil	2, p. 42-17
Dielectric Constant	1 MC 6.2 100 MC 6.1	
Power Factor	1 MC 0.0004 100 MC 0.0003	
Loss Factor	1 MC 0.002 100 MC 0.002	
Te Value	1000°C	2, p. 42-17
Modulus of Elasticity	13-15 x 10 ⁶ psi	2, p. 35-48

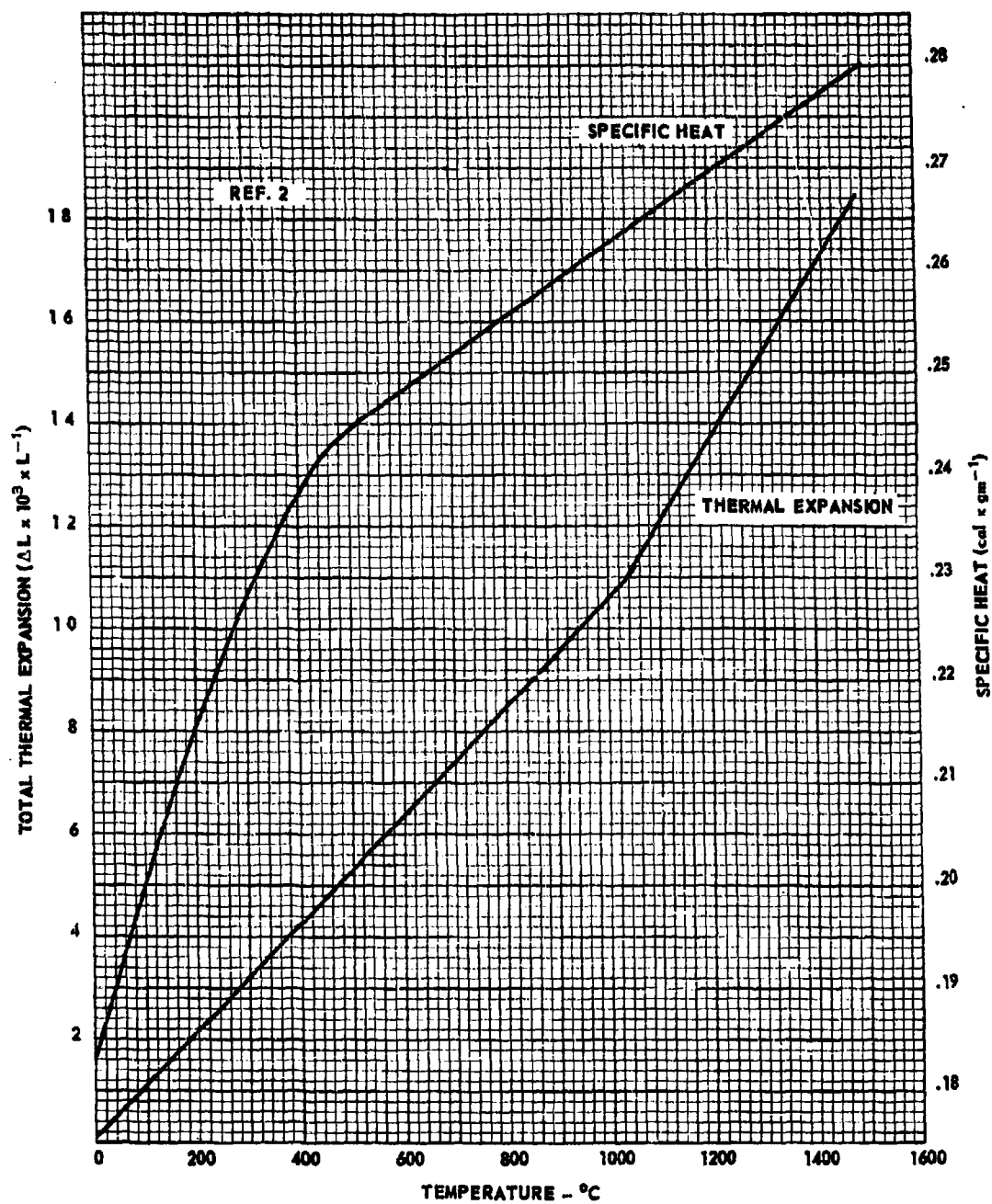


Fig. 15 - Thermal Expansion and Specific Heat of Forsterite

GOLD

Material: Gold

Chemical Composition: 99.9% min. Gold

Trade Designation: 24 Carat Gold

Suppliers: Bram Metallurgical-Chemical Co., 820 65th Ave., Philadelphia, Pa.

Handy & Harmon, 82 Fulton St., New York 38, N. Y.

J. M. Ney Co., P. O. Box 990, Hartford 1, Conn.

Western Gold & Platinum Co., 525 Harbor Blvd., Belmont, Calif.

Forms Available: Powder, wire, foil, sheet, brazing preforms, special shapes

General:

Gold is rarely used in electronic work in the massive state. It is often specified, however, as a plating or other surface coating or as a brazing material. It is used internally to suppress primary and secondary emission from tube parts and externally for appearance, corrosion and oxidation resistance, and for high electrical conductivity. The vapor pressure of gold is such that parts made from it may be operated safely at 500°C inside a vacuum envelope.

Special Handling Techniques and Formability:

In electroplating gold, the usual technique of a copper flash followed by nickel plating and then deposition of the precious metal on the surface of the nickel is sometimes inadequate. If in the application the temperature will exceed 500°C, it is recommended instead that the gold be plated

GOLD

directly on molybdenum or tungsten since there will be no inter-diffusion with these metals. If it is necessary to deposit gold on nickel wire, an intermediate layer of palladium may be used to prevent the formation of a gold-nickel alloy interface.

Cladding is sometimes recommended because of the additional thickness which may be deposited. Gold-clad tungsten and molybdenum are available commercially.

In the preparation of gold plating baths and cleaning solutions sulfur must be excluded or removed since very small traces of this element will result in serious poisoning of the cathode.

In general, brazing alloys made with gold melt at temperatures a few hundred degrees lower than similar alloys made with platinum (if in each case the precious metal is a major constituent).

Joining:

Gold can be brazed readily to itself or to other metals using silver bearing brazing alloys. The ease of spot-welding gold plated metal is usually determined by the characteristics of the base metal.

Allotropic Changes:

There are no allotropic changes on heating or cooling. The face-centered cubic structure is retained from room temperature to the melting point.

Ease of Outgassing:

Since gold is quite inert, atmospheric contaminants are not usually present in large enough quantities to cause difficulties in outgassing. A 400-450°C bakeout is adequate in nearly all cases.

Applications:

Gold internal surfaces are preferred for tubes with oxide or matrix cathodes; evaporated barium (like thorium on platinum) will diffuse away from the surface into the metal and have little effect on the work function of the gold.

Brazing alloys using gold as a major constituent are frequently used in microwave tube construction. In general, these alloys combine the advantages of availability, ease of working, good wetting and flow characteristics, low vapor pressure, excellent resistance to oxidation and reasonably good strength at elevated temperatures. Intergranular attack of nickel alloys, such as Kovar and stainless steel, is not a problem. Gold may be used alone as a brazing material or it may be alloyed with copper, nickel, palladium or platinum in either binary or ternary compositions. Some of these compositions wet tungsten and molybdenum and other high temperature metals such as Inconel and may be used for brazing these materials. Gold and its alloys simplify the making of step brazes which are often necessary in tube construction.

Besides its use inside the tube envelope, gold is sometimes found in exterior conductors and on surfaces which must remain free of oxides or other corrosion products.

GOLD

Table 7
GOLD DATA

		<u>Ref.</u>
Density	19.3 g/cc	7
Lattice Type	Face-centered cubic	15
Melting Temperature	1063°C	7
Tensile Strength	15,800 Psi	7
Modulus of Elasticity	12 x 10 ⁶ Psi	37
Maximum Elongation	25%	7
Thermal Conductivity	.70 cal/cm/sec/°C	7
Specific Heat	.031 cal/g/°C	7
Linear Thermal Expansion	14.1 in/in/°C (0 - 500°C)	7
Electrical Resistivity	2.3 x 10 ⁻⁶ ohm cm	7
Temp. Coefficient of Resistivity	39 x 10 ⁻⁴ /°C	7
Curie Point	Nonmagnetic	
Temp. for 10 ⁻⁵ mm Vapor Pressure	987°C	81

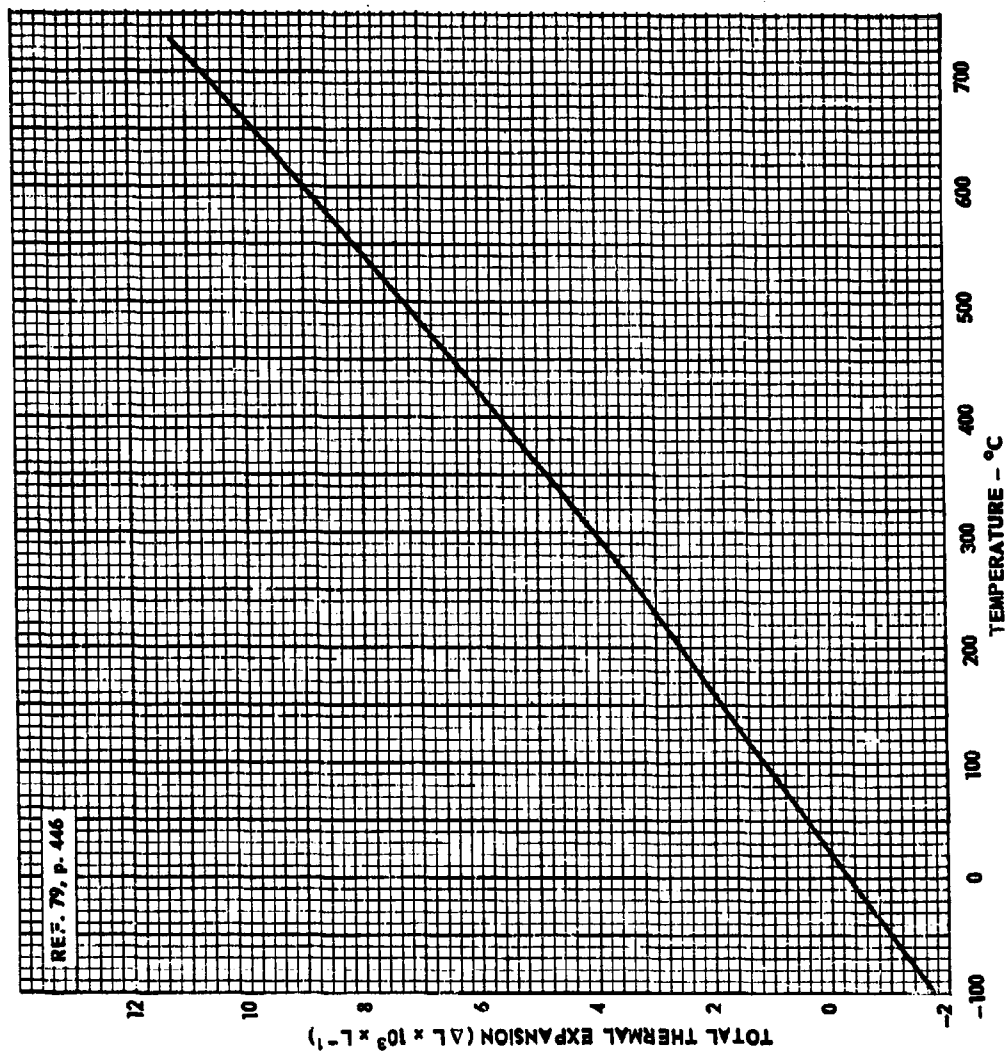


Fig. 16 — Linear Thermal Expansion of Gold

HASTELLOY B

Material: Hastelloy B*

Chemical Composition (%):

Cobalt	- 2½ Maximum	Manganese	- 1 Maximum
Chromium	- 1 Maximum	Carbon**	- .05 Maximum
Molybdenum	- 26 - 30	Vanadium	- 0.20 - 0.60
Iron	- 4 - 7	Phosphorous	- 0.04 Maximum
Sulphur	- 0.03 Maximum	Nickel	- Remainder

Trade Name: Hastelloy B

Suppliers: Haynes Stellite Co., Division of Union Carbide Corporation
Kokomo, Indiana.

Forms Available: Sheet, plate, bar, wire and rod.

General:

Hastelloy B is an austenitic non-magnetic alloy similar in many ways to the 300 series stainless steels. It should be handled somewhat like the stainless steels, but since it has higher strength and lower ductility, some forming operations will be more difficult. Shop procedures must allow for the fact that this material hardens rapidly on cold-working.

Special Handling Techniques and Formability:

This alloy is somewhat brittle between the temperatures of 650 - 980°C. Aging in this temperature range increases both strength and hardness but reduces ductility and causes precipitation along the grain boundaries.

*Hastelloy B is a trademark of the Union Carbide Corporation

**Carbon .05% Maximum - Wrought Material; 0.12% Maximum in Cast Material

This precipitation causes embrittlement and loss of corrosion resistance. A solution heat treatment at temperatures from 1150 to 1180°C for five to thirty minutes followed by a rapid quench in air or water restores ductility and relieves stress. Close temperature control is necessary; overheating even by 15 - 30°C will reduce tensile strength and corrosion resistance; also any residue of grease or graphite which has been left on the surfaces will cause carburization with consequent embrittlement. Sulphur content of furnace atmospheres should be kept low.

It is recommended that parts made of Hastelloy B be given a final annealing after the last forming operation in order to relieve stresses. In machining, tungsten carbide tools are used for turning. A surface speed of about 35 - 50 f.p.m. and an 8 - 15 mil roughing cut is adequate. Finishing cuts run about 5 - 8 mils; lighter cuts may lead to excessive surface hardening. Tapping is not recommended.

Joining

The molybdenum-nickel alloys such as Hastelloy B may be spot-welded or brazed. Surfaces should be pickled and, if necessary, buffed, immediately before welding. Silver solder makes an effective brazing alloy. Components after brazing should be cooled rapidly but not quenched. Holding at brazing temperature for periods which are longer than necessary can produce excessive grain growth.

Allotropic Changes

There are no changes in crystal form on heating or cooling, but as noted under "Special Handling", grain growth may be a problem.

Ease of Outgassing:

Thin-walled parts may be outgassed by rapid heating to about 1000°C for two to ten minutes; parts should be cooled rather quickly. A preliminary firing in dry hydrogen, perhaps as part of the heat treatment, will aid in removing oxygen and nitrogen,

Applications:

Hastelloy B, because of its high strength and rigidity, can sometimes be substituted for molybdenum or tungsten in making grids and supports. Its dimensional stability is such that grid spacings can be held within narrow tolerances even at several hundred degrees centigrade.

Cleaning:

Mechanical cleaning procedures are more effective with Hastelloy B than are acid cleaning techniques. The oxide film which forms on this alloy is very inert. If chemical cleaning methods are to be used, the first treatment should consist of a one to two minute dip in melted caustic at about 425°C followed by a water wash, an acid dip, and a final rinse in water. The acid bath should contain about 7% sulfuric acid and about $\frac{1}{2}$ % hydrochloric acid (by volume).

HASTELLOY B

Table 8
HASTELLOY B DATA

		<u>Ref.</u>
Density	9.24 g/cc	7
Lattice Type	Face-centered cubic	58
Melting Temperature	1320° - 1350°C	58
Annealing Temperature	1160°C	58
Tensile Strength	121,000 Psi (rolled) 70,000 Psi (cast)	7
Yield Strength	55,000 Psi at room temp.	7
Modulus of Elasticity	29.5 x 10 ⁶ Psi at room temp.	58
Maximum Elongation	42%	7
Thermal Conductivity	.027 cal/cm ² /cm/°C/sec	7
Specific Heat	.091 cal/gm/°C	7
Linear Thermal Expansion	14.6 x 10 ⁻⁶ in/in/°C (0 - 1000°C)	15, p. 1055
Electrical Resistivity	135 x 10 ⁻⁶ ohm-cm at 20°C	7
Temp. for 10 ⁻⁵ mm Vapor Pressure	1185°C	73
Magnetic Permeability	1 - 1.001	58

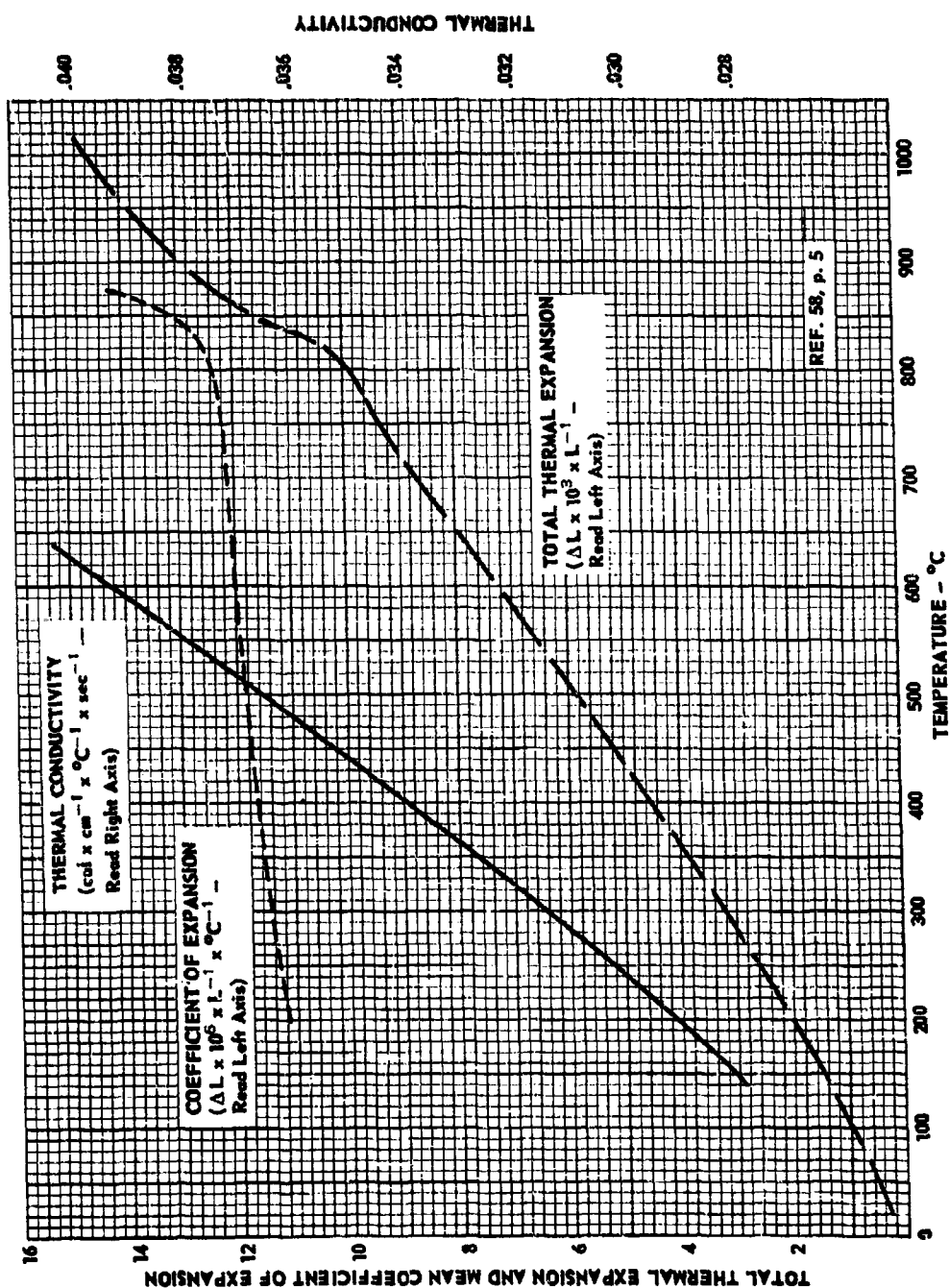


Fig. 17 — Linear Thermal Expansion, Mean Coefficient of Expansion and Thermal Conductivity of Hastelloy B

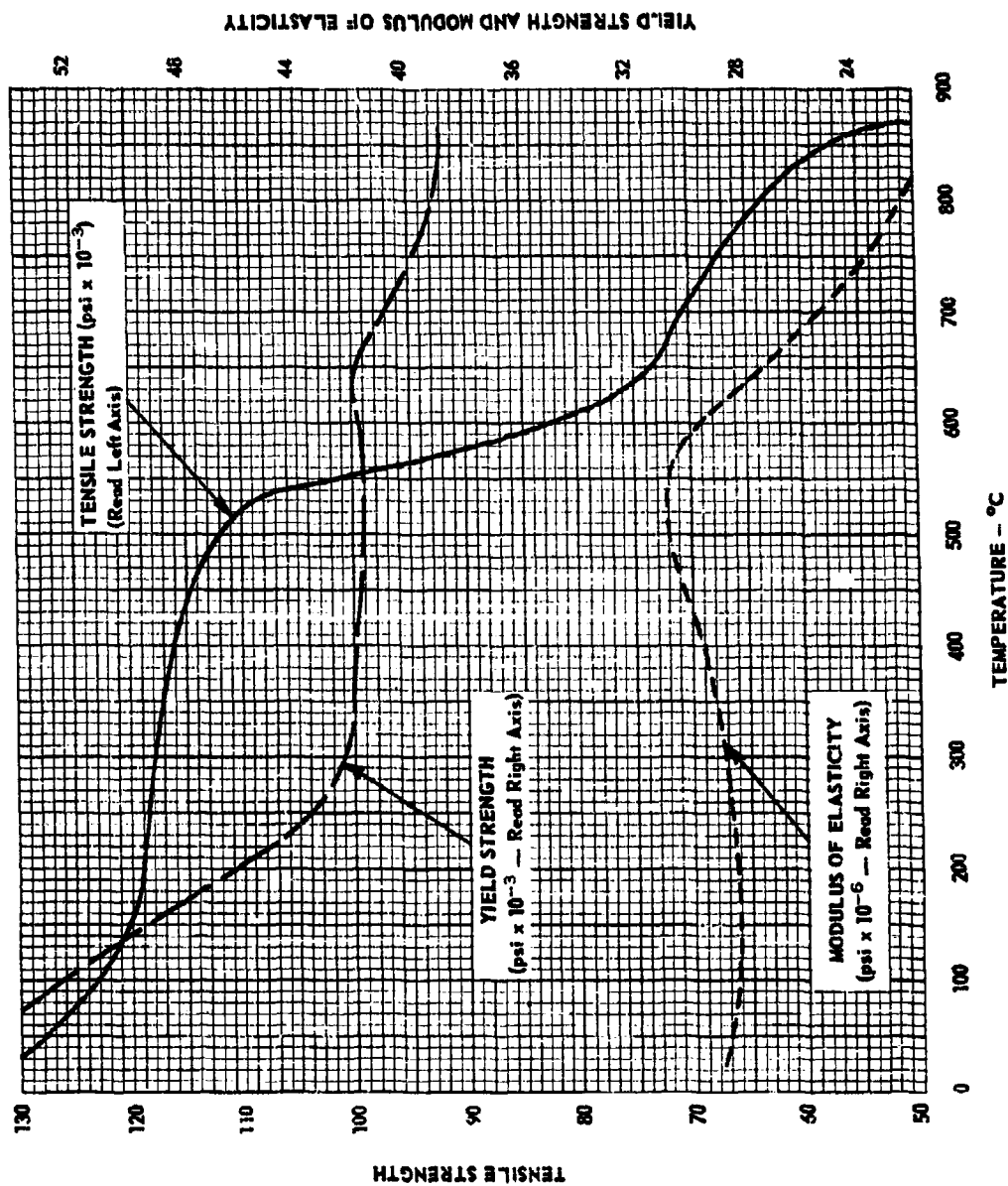


Fig. 18 — Tensile Strength, Yield Strength and Modulus of Elasticity of Hastelloy B

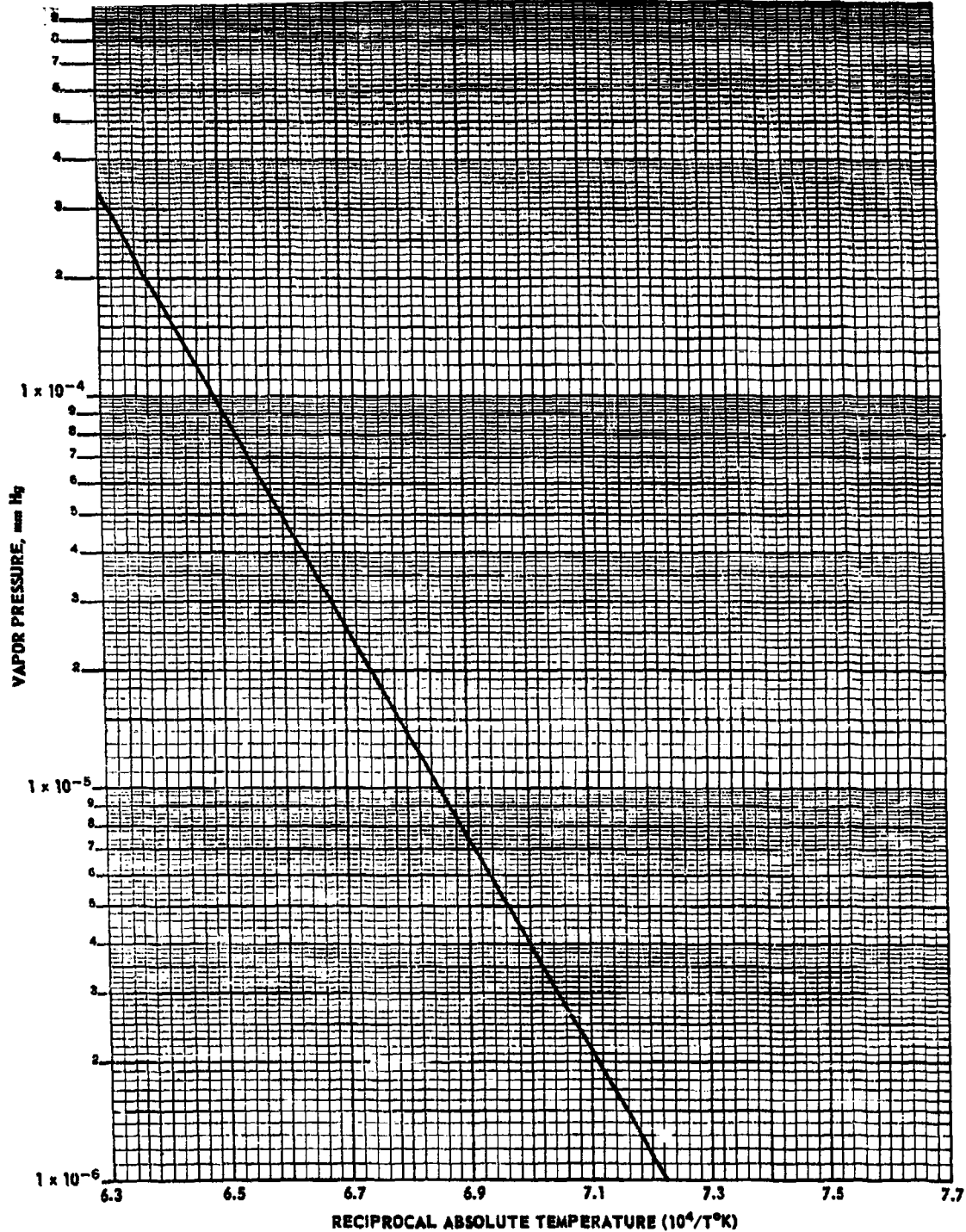


Fig. 19 — Vapor Pressure of Hastelloy B

Material: Inconel

Chemical Composition: (Nominal %)

Nickel+Cobalt	- 76.4	Sulfur	- 0.007
Carbon	- 0.04	Silicon	- 0.20
Manganese	- 0.20	Copper	- 0.10
Iron	- 7.2	Chromium	- 15.8

Trade Name: Inconel*

Supplier: The International Nickel Co., 67 Wall St., New York 5, N. Y.

Forms Available: Sheet, strip, rod, bar, tube, wire, plate and screen

General:

Inconel (nickel-chromium alloy) is practically non-magnetic and is resistant to oxidation at elevated temperature. It also possesses higher tolerance for sulfur-bearing atmospheres at heat-treating temperatures than nickel, stainless steel or copper. The oxide surface which forms at high temperature is tightly adherent and forms an adequate protective layer in most applications. The cold-worked and stress equalized material shows low relaxation at temperatures up to 350°C even at high stresses for long times. It may be used as a spring element for high temperatures (up to 400-450°C) if stresses are not excessive and if long life is not required. Inconel work hardens more rapidly than nickel or Monel, but may be readily fabricated. Stress relief takes place at 450-480°C in about one-half to one hour.

*T. M. Reg. - International Nickel Co.

INCONEL

Special Handling Techniques and Formability:

Inconel, unlike Inconel X, is not an age-hardening alloy. The annealed material may be hardened only by cold-working. Annealing begins at 870°C; complete annealing takes place in ten to fifteen minutes at about 980°C. Since the rate of cooling is not critical, the alloy may be either quenched or furnace-cooled with about the same results.

Chromium oxide (Cr_2O_3) begins to form at about 350°C in furnace atmospheres containing oxygen, water vapor, carbon monoxide or carbon dioxide. This oxide film may be removed by grinding or pickling.

Joining:

The oxides of chromium, aluminum and titanium are inert and refractory. None of them are reduced in a normal copper-brazing atmosphere. Alloys such as Inconel, Inconel X and "K" Monel are, therefore, more difficult to braze than most metals encountered in electron tube work. To prevent the formation of these refractory oxides, the parts may be copper or nickel-plated before brazing; it may be necessary to use anodic-cathodic strike treatment while plating. Ideally, brazing should take place in a vacuum of the order of 10^{-5} mm Hg or less rather than in a hydrogen atmosphere.

Allotropic Changes:

There are no changes in crystal form on heating or cooling. Grain growth becomes fairly rapid, however, at temperatures about 870°C.

Ease of Outgassing:

Inconel which has been fired for twenty minutes at 1000°C in dry hydrogen may be outgassed by heating to 800 to 1000°C for ten to twenty minutes. The formation of a surface oxide layer does not prevent outgassing but may be objectionable if appearance is a factor.

Applications:

This alloy is used predominately for spring applications such as cathode-ray tube spiders, tube supports, diaphragms and bellows. It is also recommended where high tensile stresses may be encountered (up to 80,000 psi at 500°C).

Oxidation:

Inconel is characterized by high strength and resistance to catastrophic oxidation at temperatures as high as 1000°C in air. There is no inter-granular oxidation.

INCONEL

Table 9
INCONEL DATA

		<u>Ref.</u>
Density	8.47 g/cc	52
Melting Temperature	1395°C	44
Annealing Temperature	980°C	29
Tensile Strength	98,000 Psi	44
Yield Strength	33,000 Psi	44
Modulus of Elasticity	31×10^6 Psi	44
Maximum Elongation	42%	44
Thermal Conductivity	.036 cal/cm/sec/°C	7
Specific Heat	.109 cal/g/°C	7
Linear Thermal Expansion	11.5×10^{-6} in/in/°C	7
Electrical Resistivity	98×10^{-6} ohm-cm at 20°C	44
Temp. Coefficient of Resistivity	$.000125 \times 10^{-6}/°C$	15, p. 1057
Curie Point	-40°C	15, p. 1057
Magnetic Permeability	1.006 (H = 200 oersteds)	44

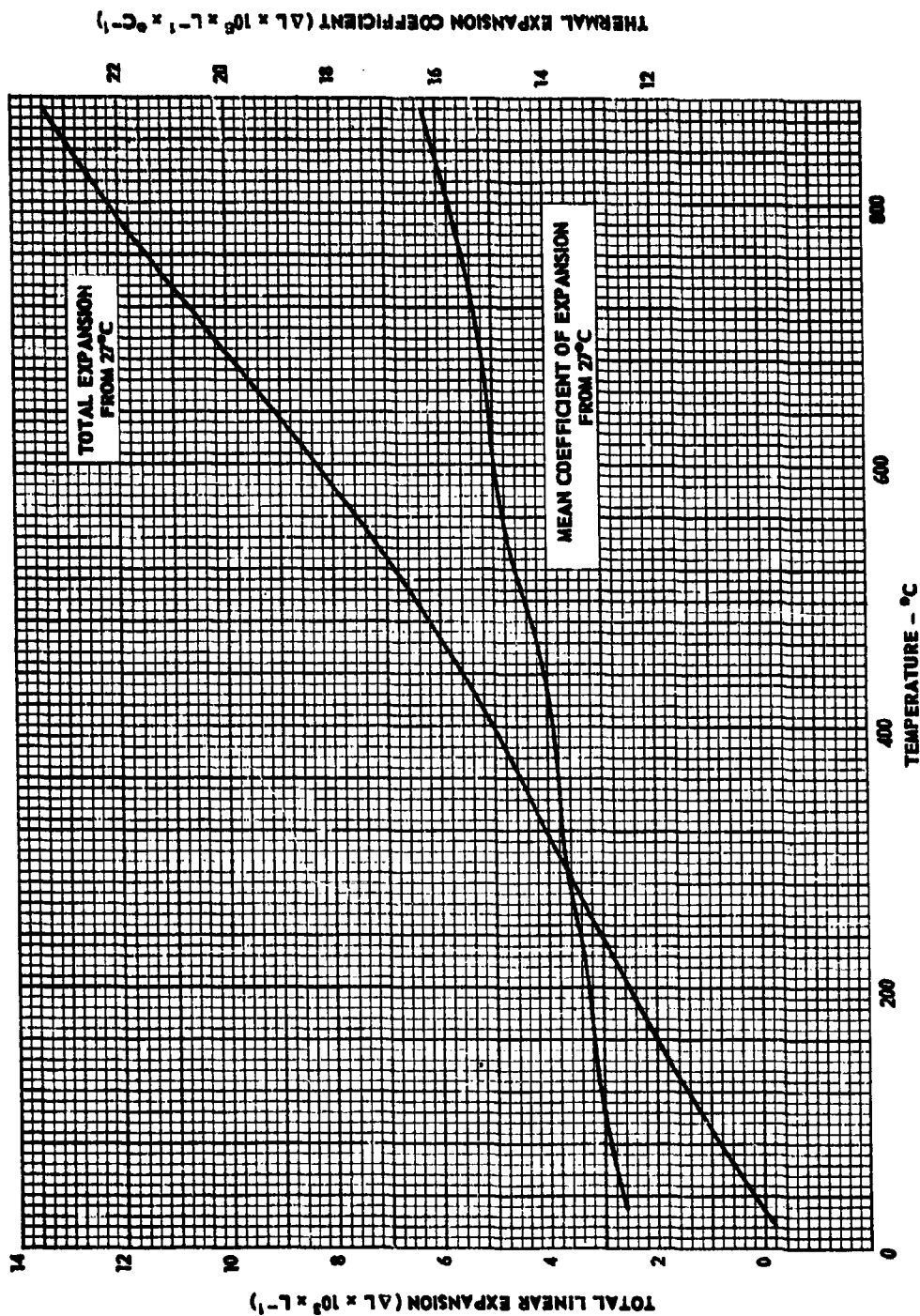


Fig. 20 — Linear Thermal Expansion and Mean Coefficient of Expansion of Inconel

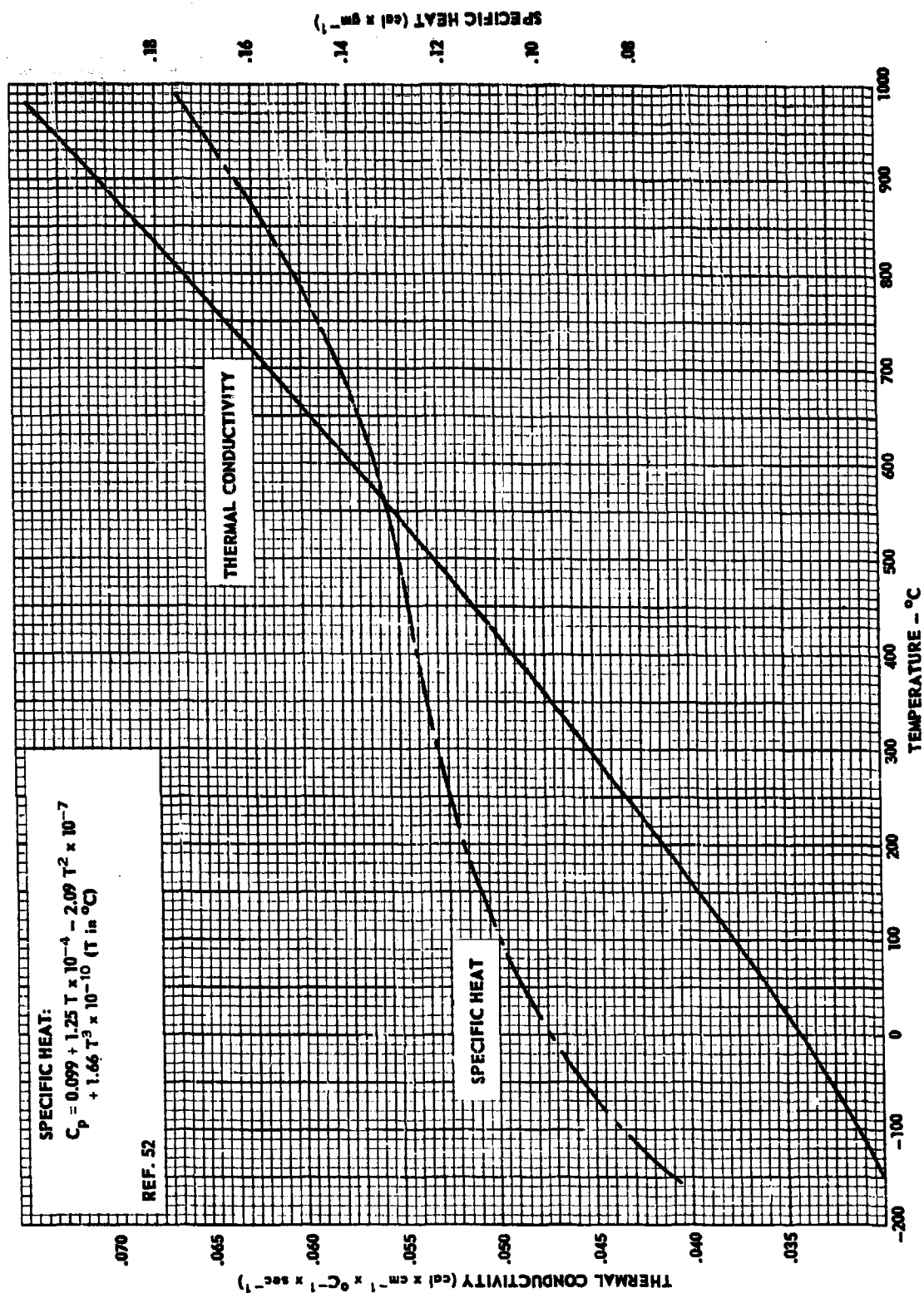


Fig. 21 — Specific Heat and Thermal Conductivity of Inconel

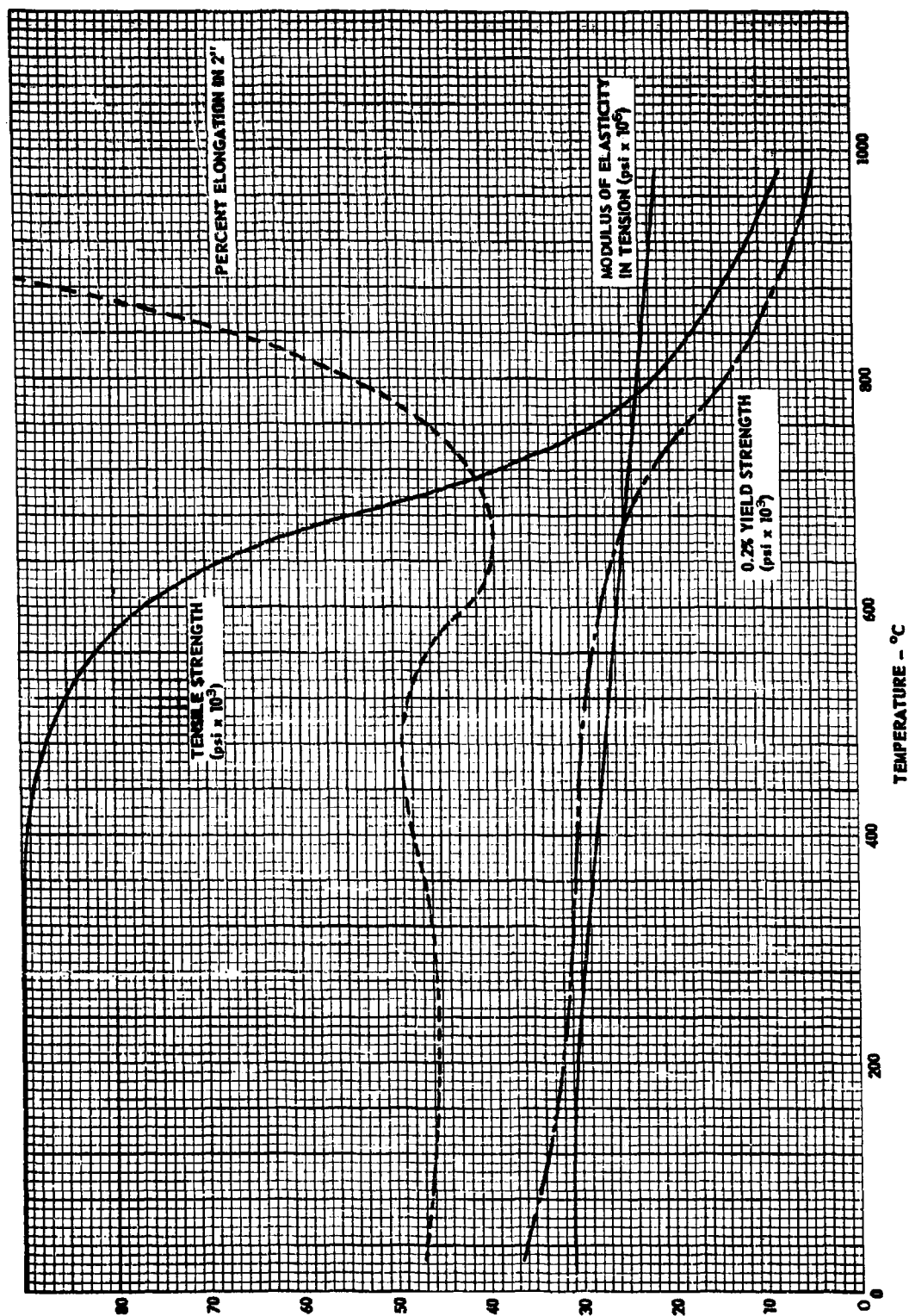


Fig. 22 -- Mechanical Properties of Inconel

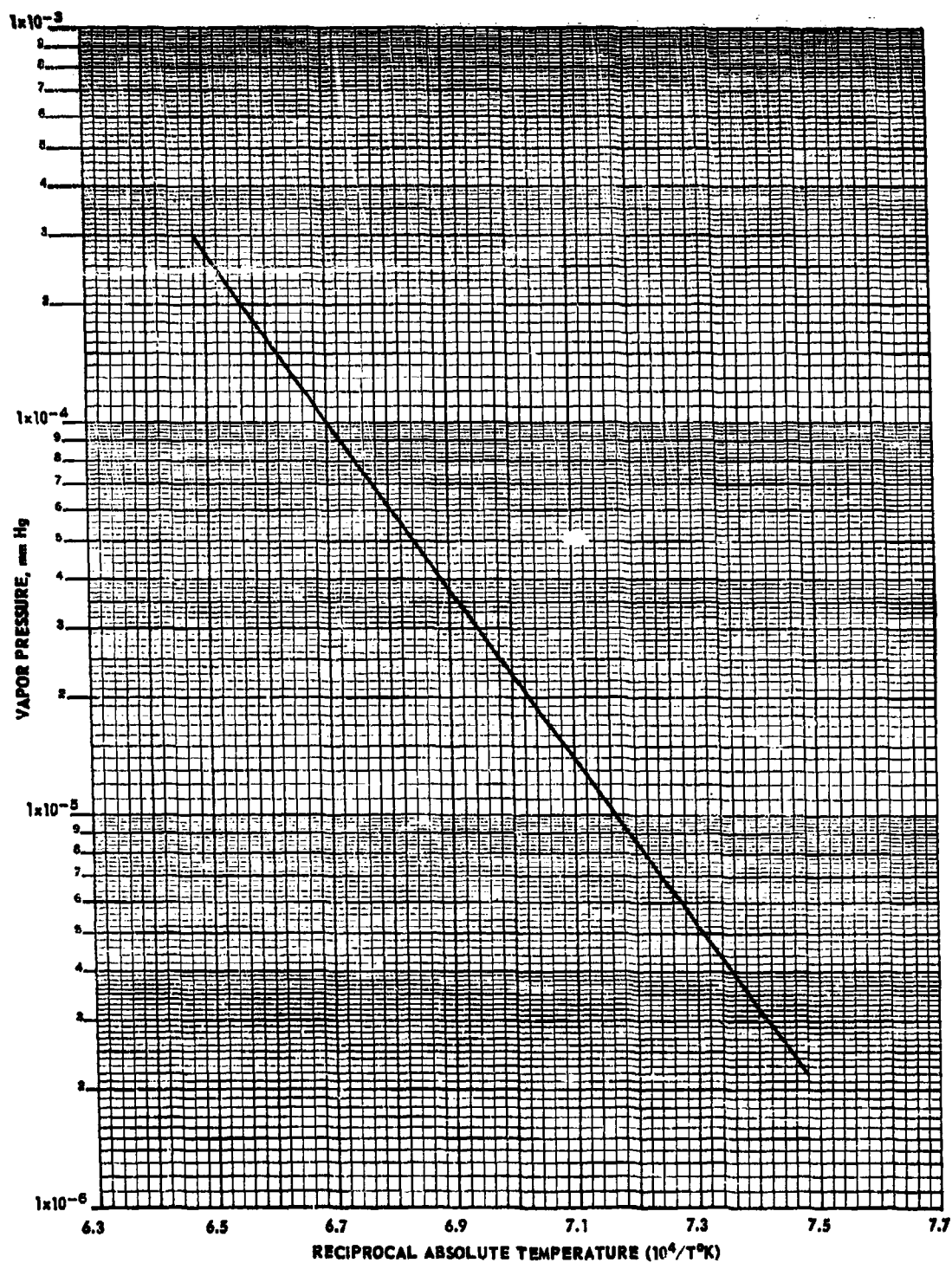


Fig. 23 — Vapor Pressure of Inconel

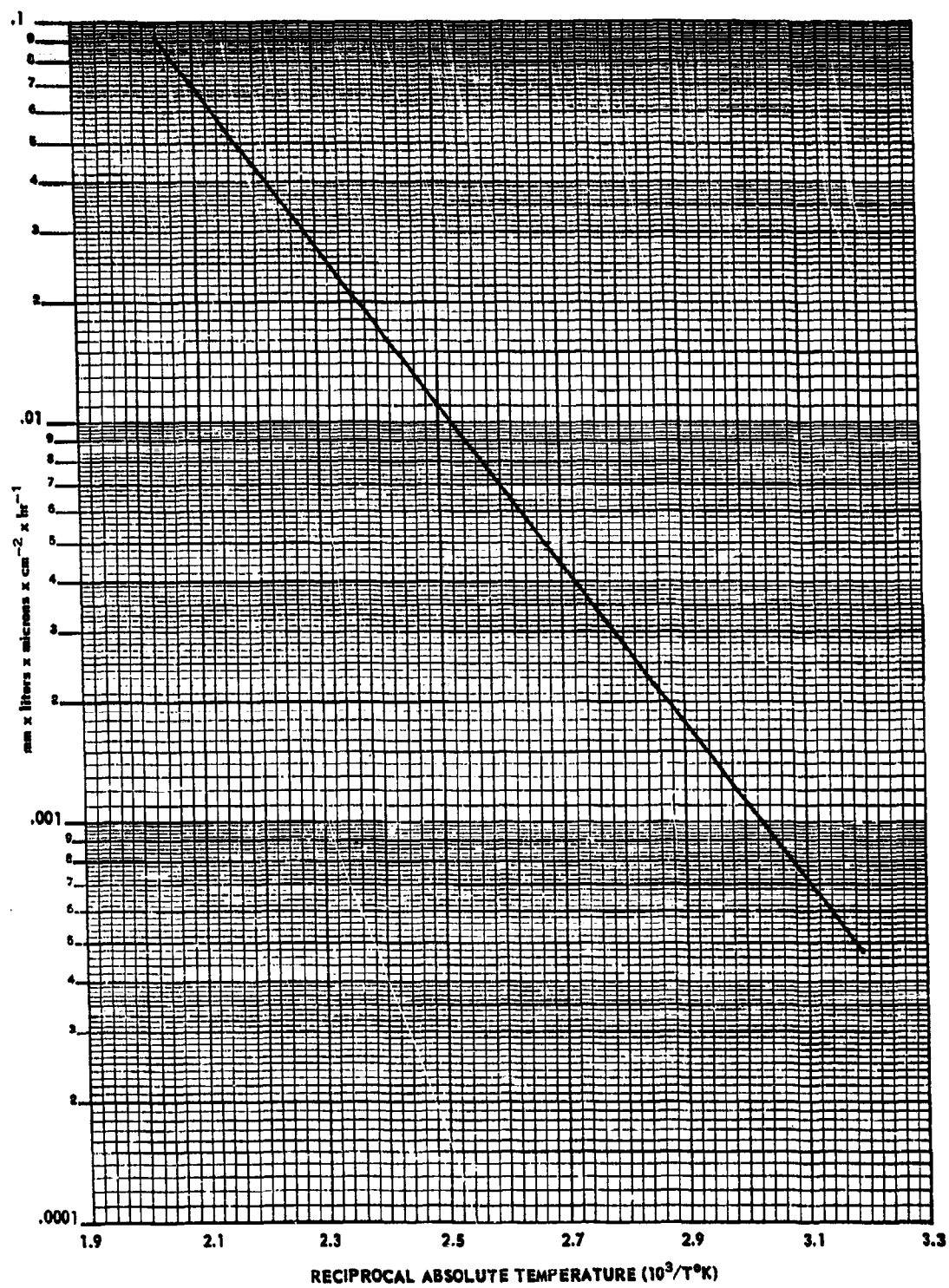


Fig. 24 — Hydrogen Permeation Through Inconel

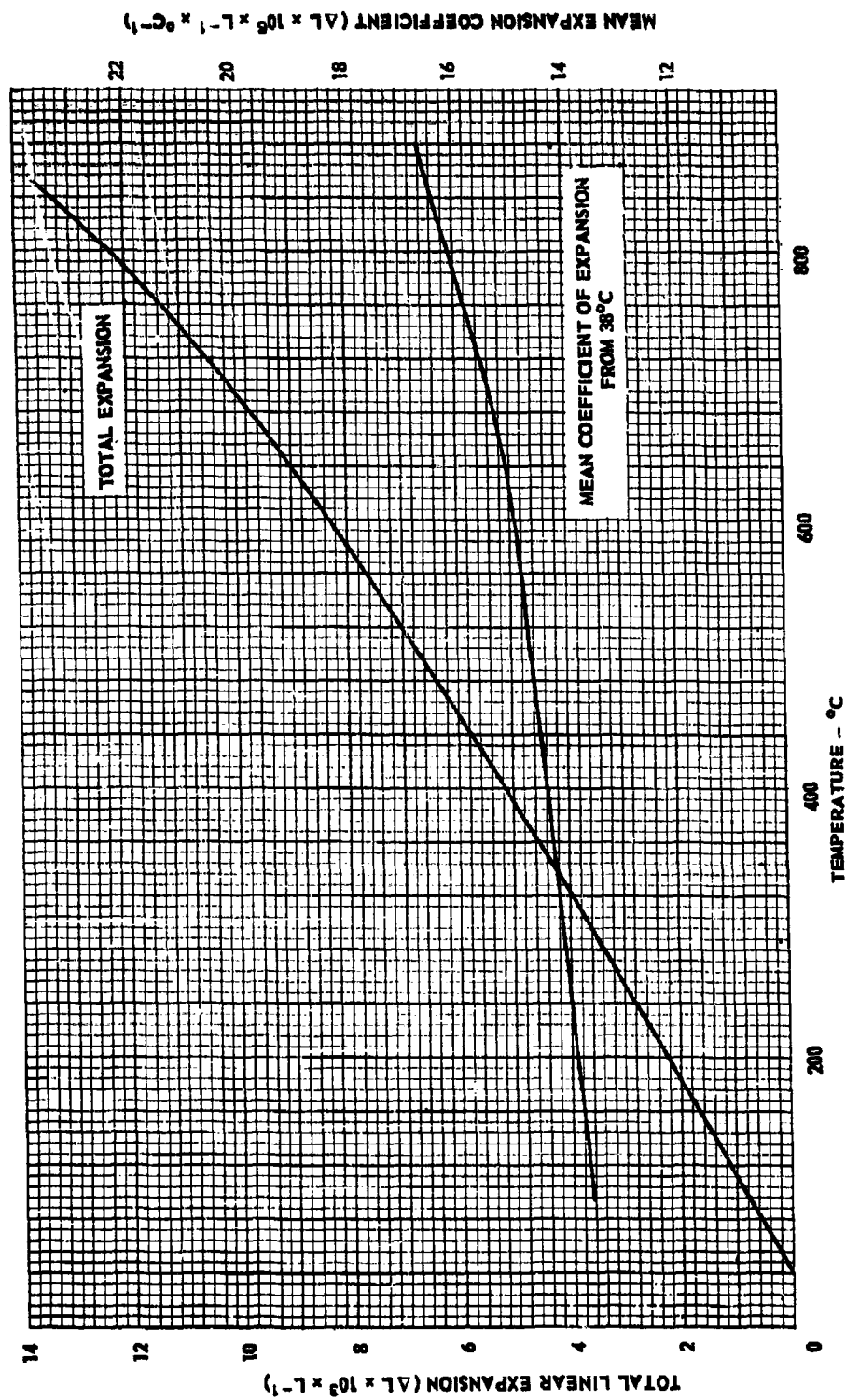


Fig. 25 — Linear Thermal Expansion and Mean Coefficient of Expansion for Inconel X

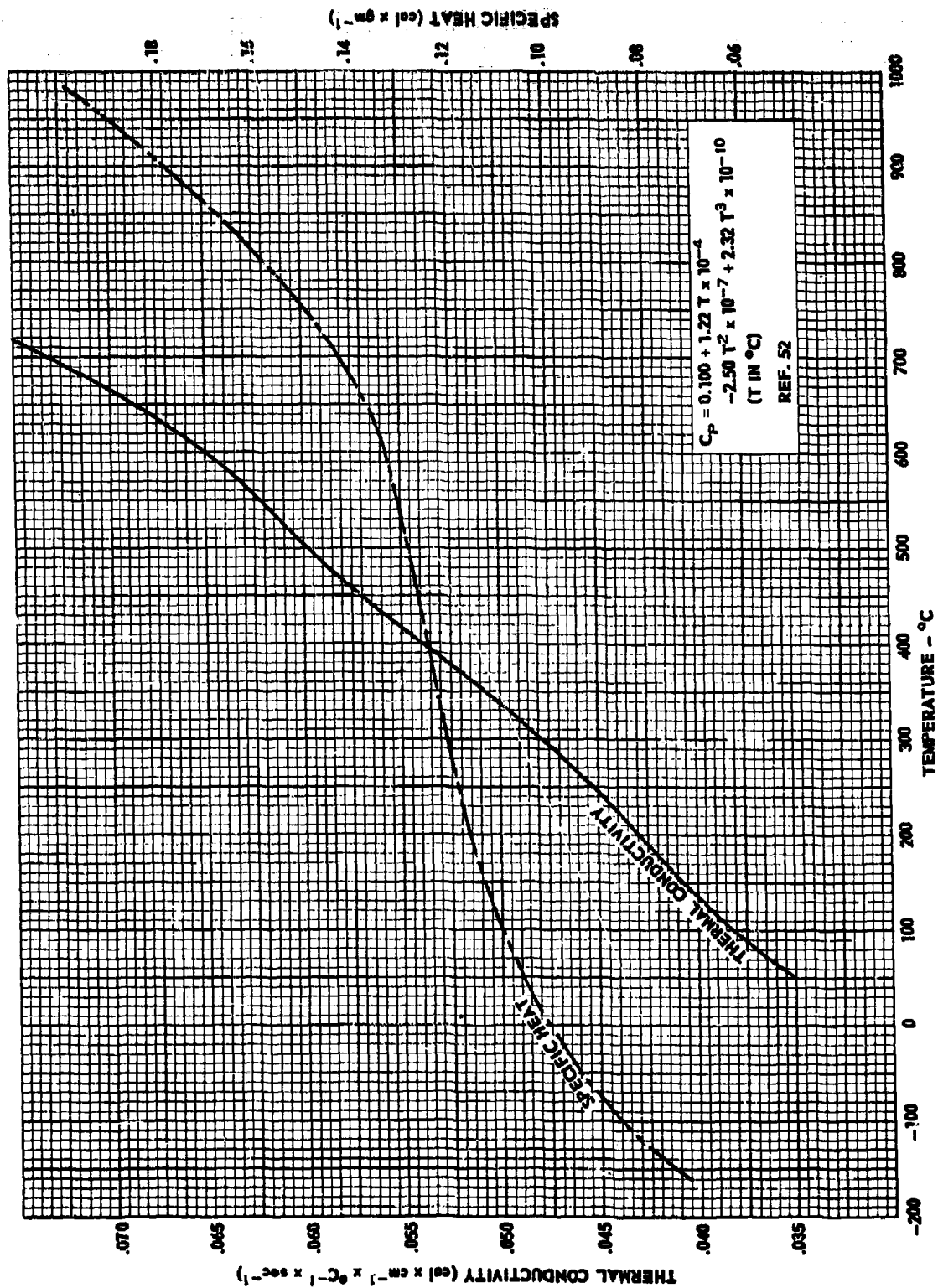


Fig. 26 — Specific Heat and Thermal Conductivity of Inconel X

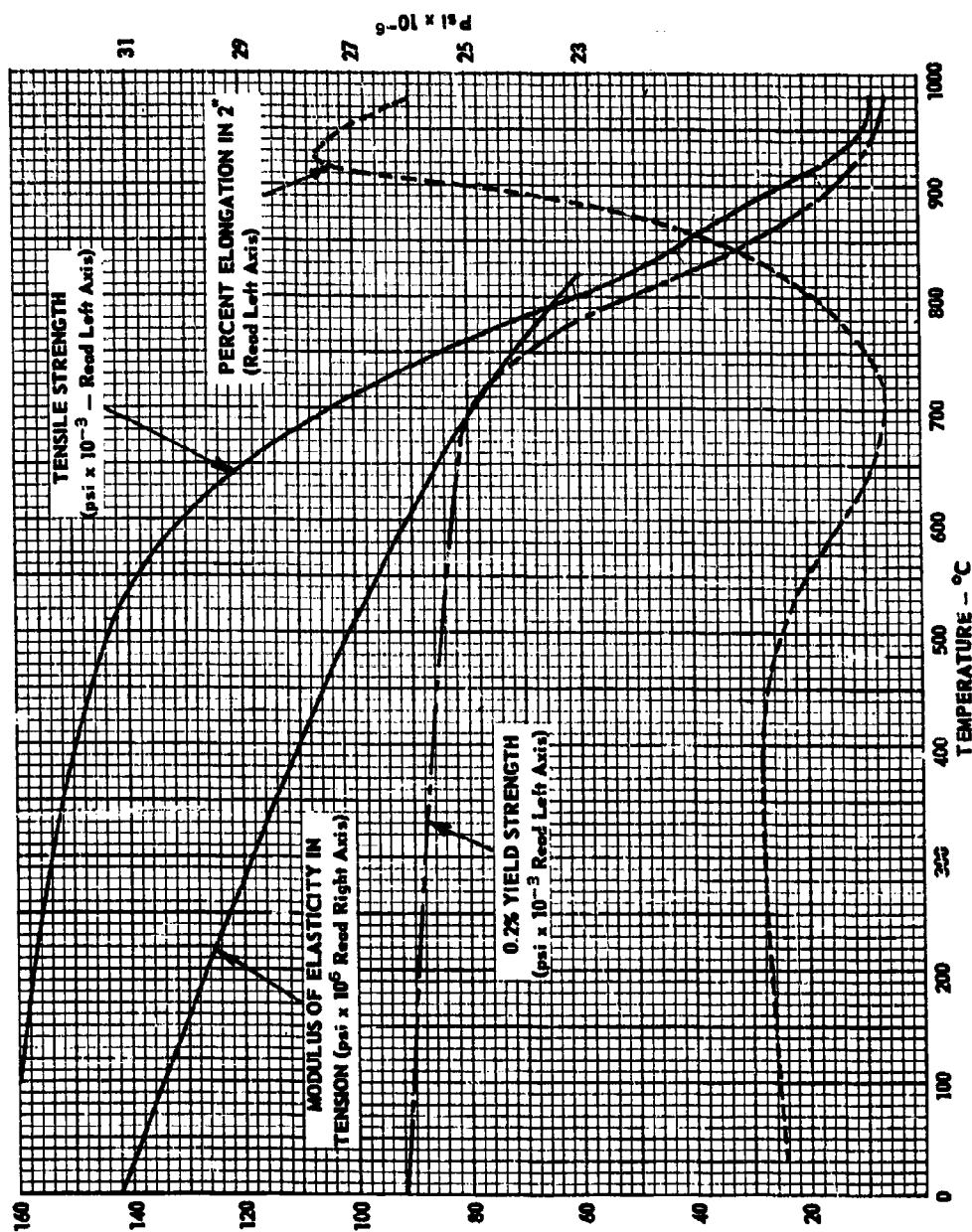


Fig. 27 - Mechanical Properties of Inconel X

Material: Iron (High Purity)

Chemical Composition:

Iron	- 99.8 min.
Carbon	- 0.03 max..
Silicon	- 0.01 max..
Manganese	- 0.04 max.

Trade Designations: Armco iron, Svea iron, carbonyl iron, Ommet iron

Suppliers: Armco Steel Corp., Middletown, Ohio

George W. Prentice & Co., Holyoke, Mass.

Forms Available: Wire, bar, rod, sheet, strip, tube, powder

General:

Iron has a moderately low vapor pressure - in the same range as nickel - but cathode sputtering is less of a problem than with nickel. Pure iron has considerably higher corrosion resistance than commercial iron, but still must be protected if stored for any length of time in air. Oxide coatings, however, are easily reduced by firing in hydrogen or high vacuum at 900-950°C.

Special Handling Techniques and Formability:

Iron becomes brittle between 850°-1050°C and should not be deformed in this temperature range. Most working is done at room temperature in order to avoid oxidation. Pure iron will soften considerably above 500°C leading to complete softening at normal outgassing temperatures. The ductility of iron at room temperature is not as high as that of nickel; this makes deep

IRON

drawing more difficult, but iron is easy to bend and fold and it rolls easily and polishes to a high lustre. Turning and cutting operations are quite difficult because of the high ductility and plasticity.

Joining:

Iron may be spot-welded, brazed or welded. Silver or copper or their alloys may be used for brazing, but sulfur or phosphorus must be avoided.

Allotropic Changes:

Body-centered cubic alpha iron changes to face-centered gamma iron at about 900°C and on heating to 1400°C , this in turn, changes to delta iron which is also body-centered cubic.

Ease of Outgassing:

Iron can be effectively outgassed by hydrogen firing at $950^{\circ}\text{--}1000^{\circ}\text{C}$ for ten to thirty minutes, then heating to about the same temperature for two to ten minutes in vacuum.

Applications:

Soft iron or high purity iron is widely used because of its unique combination of high permeability and saturation induction with low coercive force. It is therefore used in microwave tubes for magnetron pole pieces, magnet stack shims for traveling-wave tubes, and shielding where high flux densities occur. It is also used for electrodes and support wires in electron tubes, sometimes replacing nickel in this application; in mercury vapor tubes and other ion tubes, hot-cathode rectifiers, glow discharge rectifiers, etc.

IRON

Table 10
IRON DATA

		<u>Ref.</u>
Density	7.87 g/cc	7
Lattice Type	Body-centered cubic	78
Melting Temperature	1537°C	7
Tensile Strength	35,000 Psi	78
Modulus of Elasticity	30×10^6 Psi	78
Yield Strength	15,000 Psi	78
Maximum Elongation	54%	78
Thermal Conductivity	.17 cal/cm/sec/°C	7
Specific Heat	.109 cal/g°C	7
Linear Thermal Expansion	13.8×10^{-6} in/in/°C	15, p. 427
Electrical Resistivity	9.71×10^{-6} ohm-cm	7
Temp. Coefficient of Resistivity	$65.1 \times 10^{-4}/°C$	7
Curie Point	768°C	15, p. 425
Electron Work Function	4.48 eV	50
Richardson Constant 'A'	26	50
Temp. for 10^{-5} mm Vapor Pressure	1107°C	81

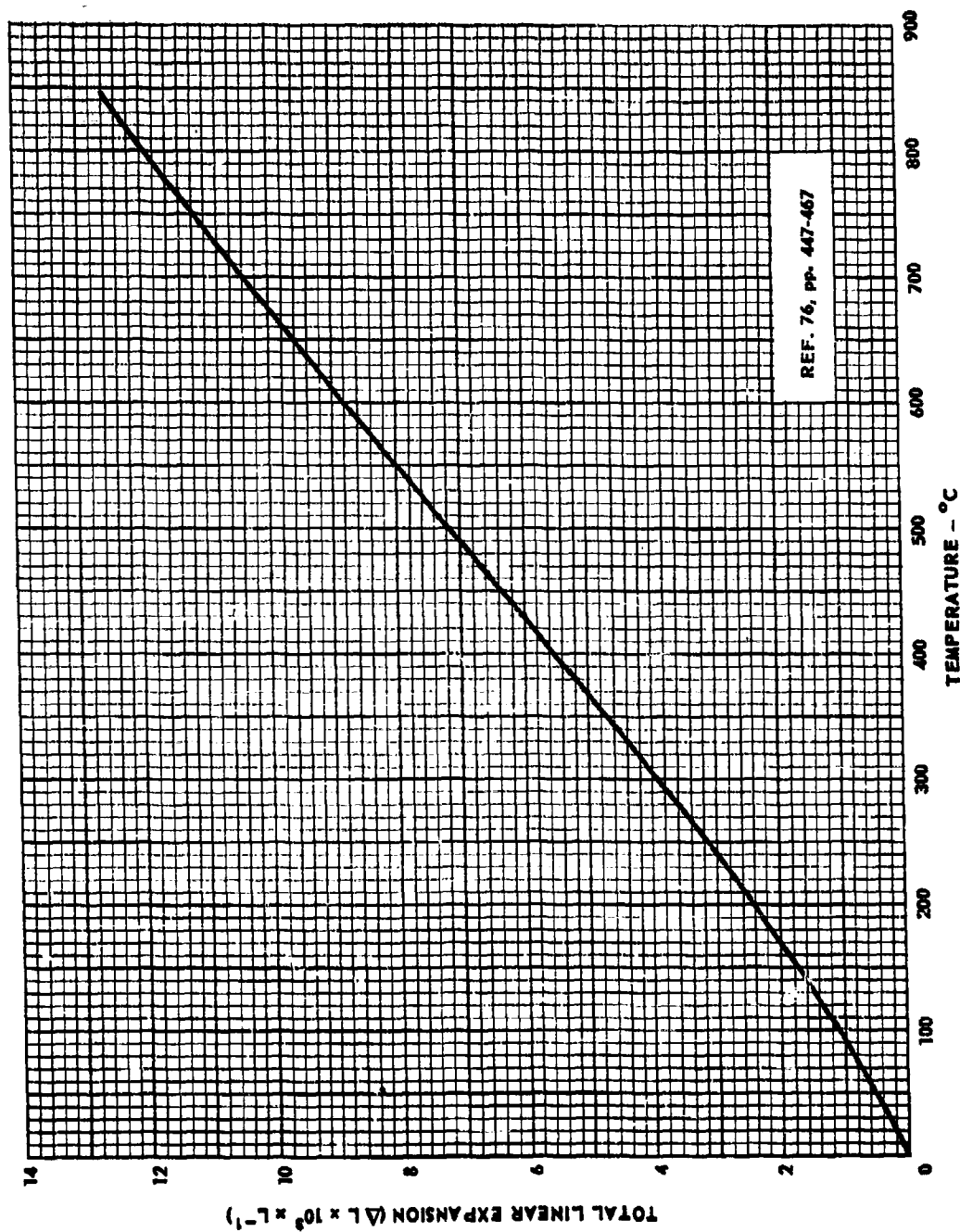


Fig. 28 — Linear Thermal Expansion of Iron

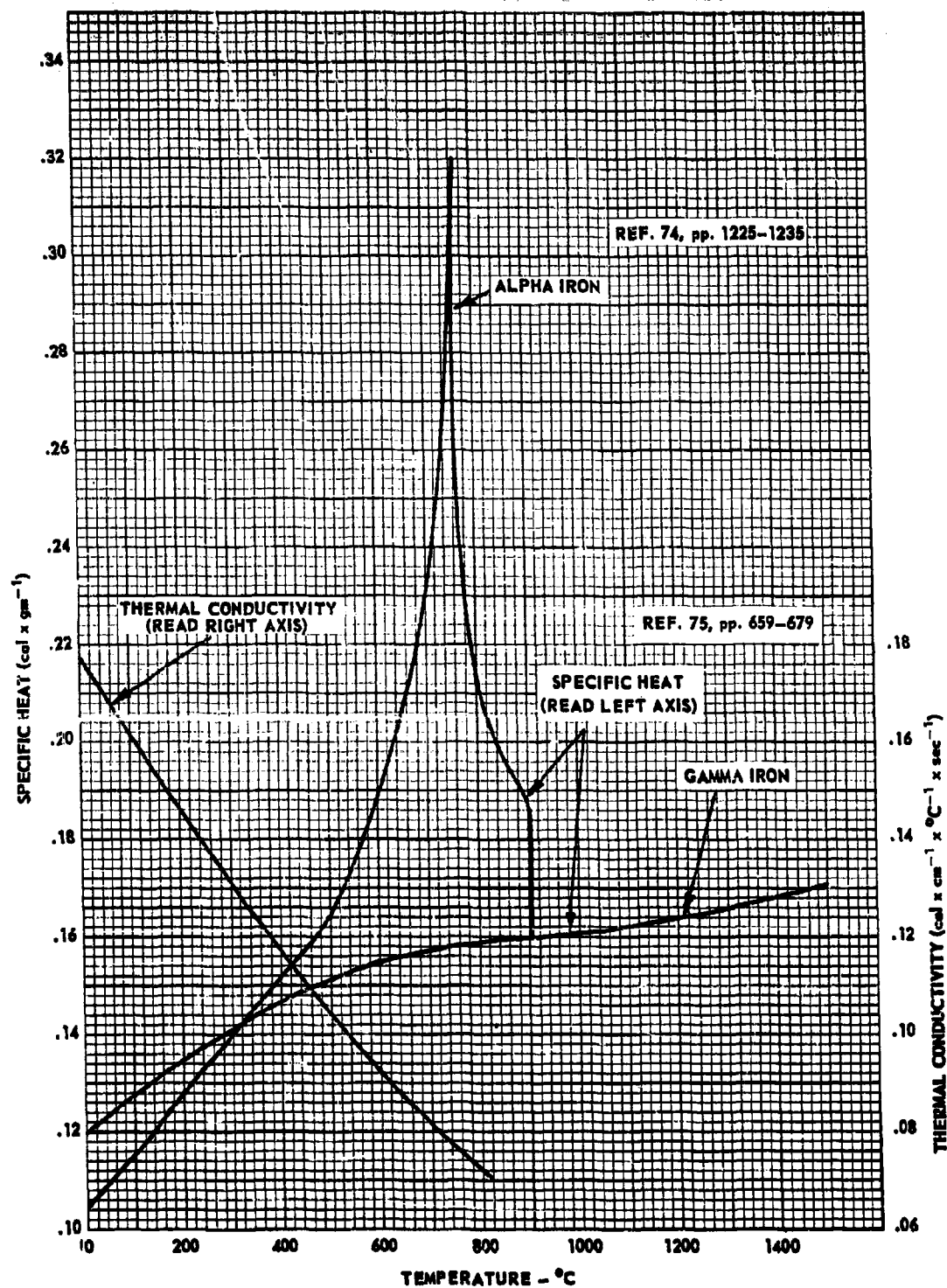


Fig. 29 — Specific Heat and Thermal Conductivity of Iron

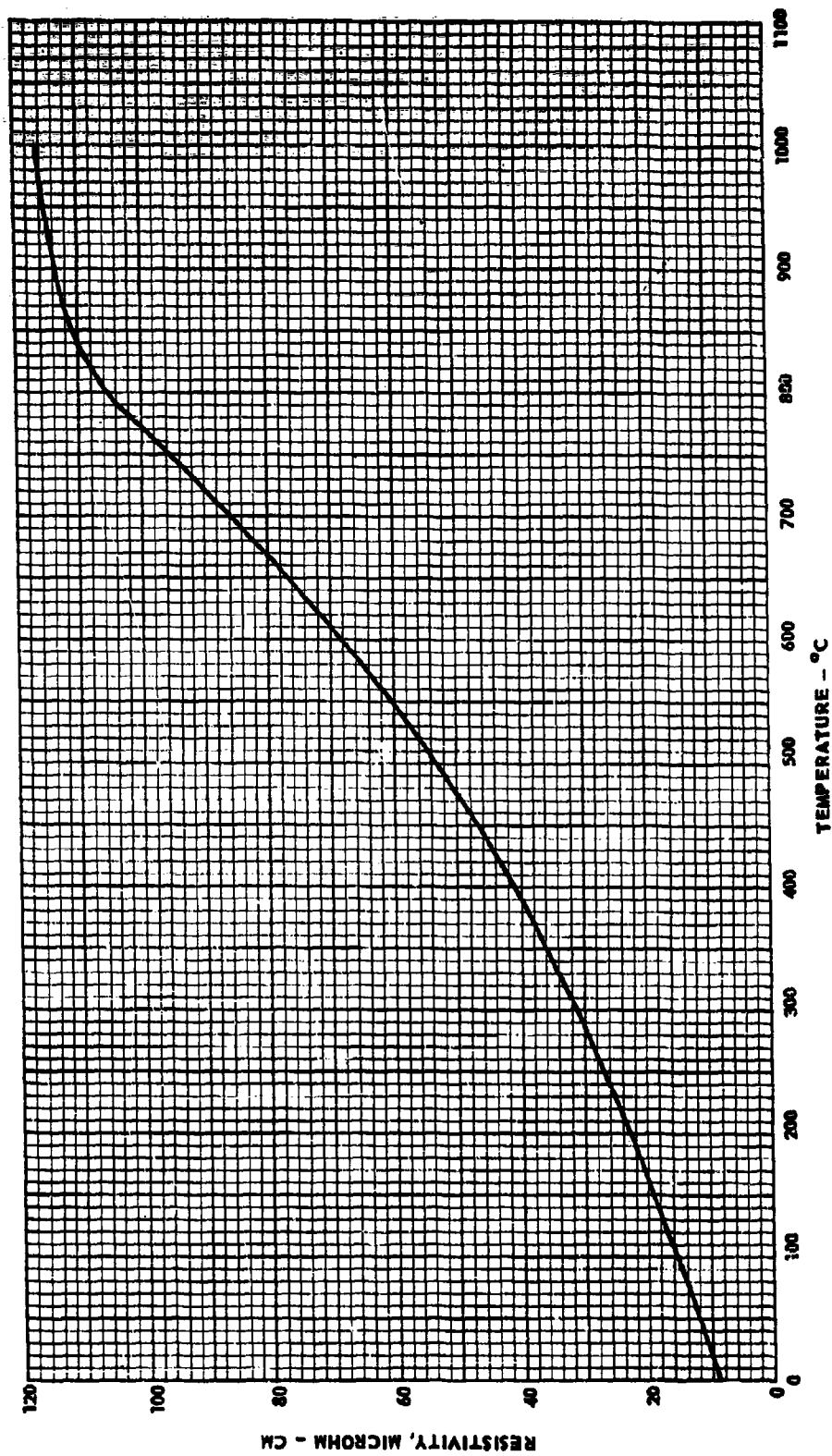


Fig. 30 -- Electrical Resistivity of Iron

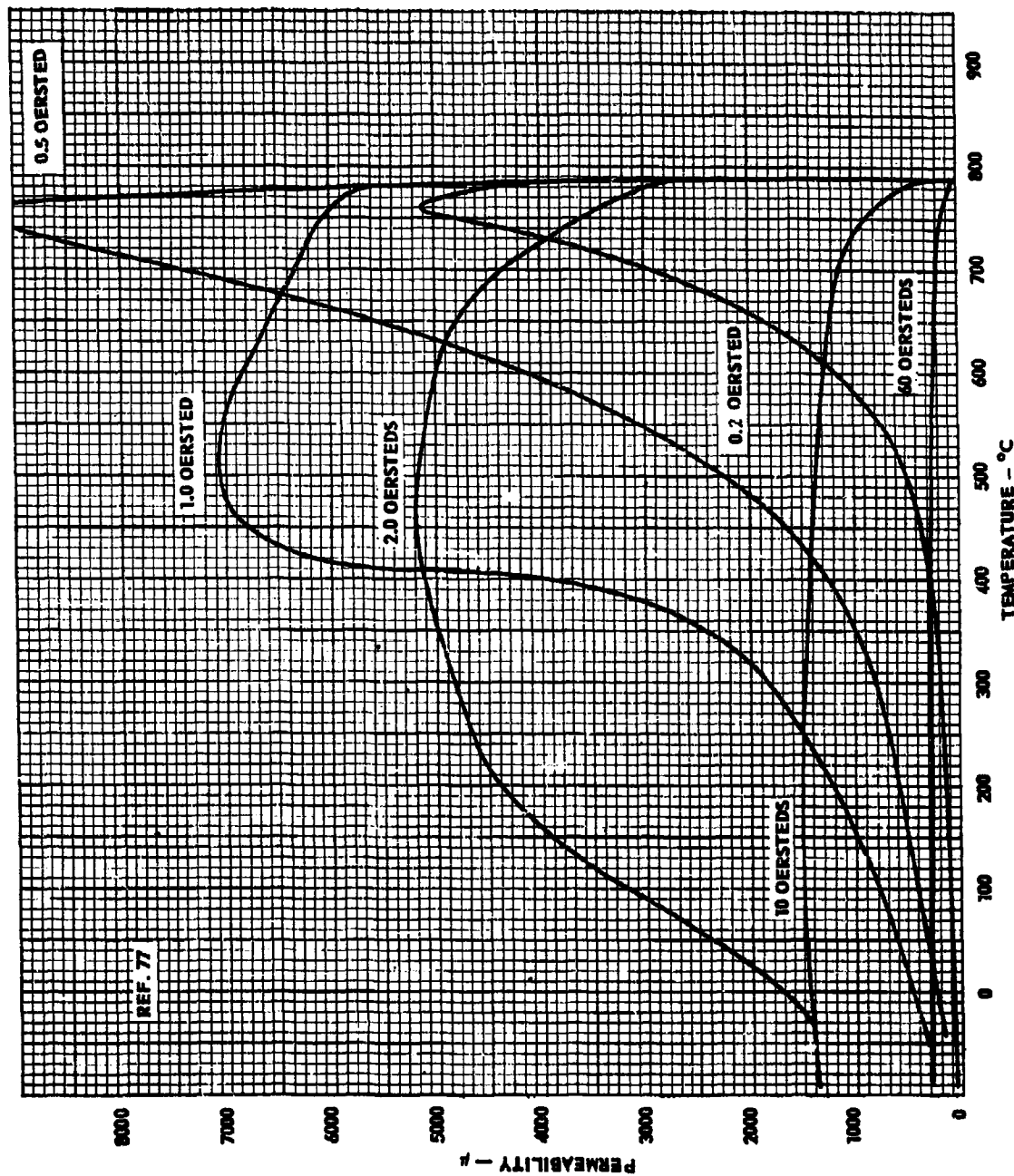


Fig. 31 — Magnetic Permeability of Iron

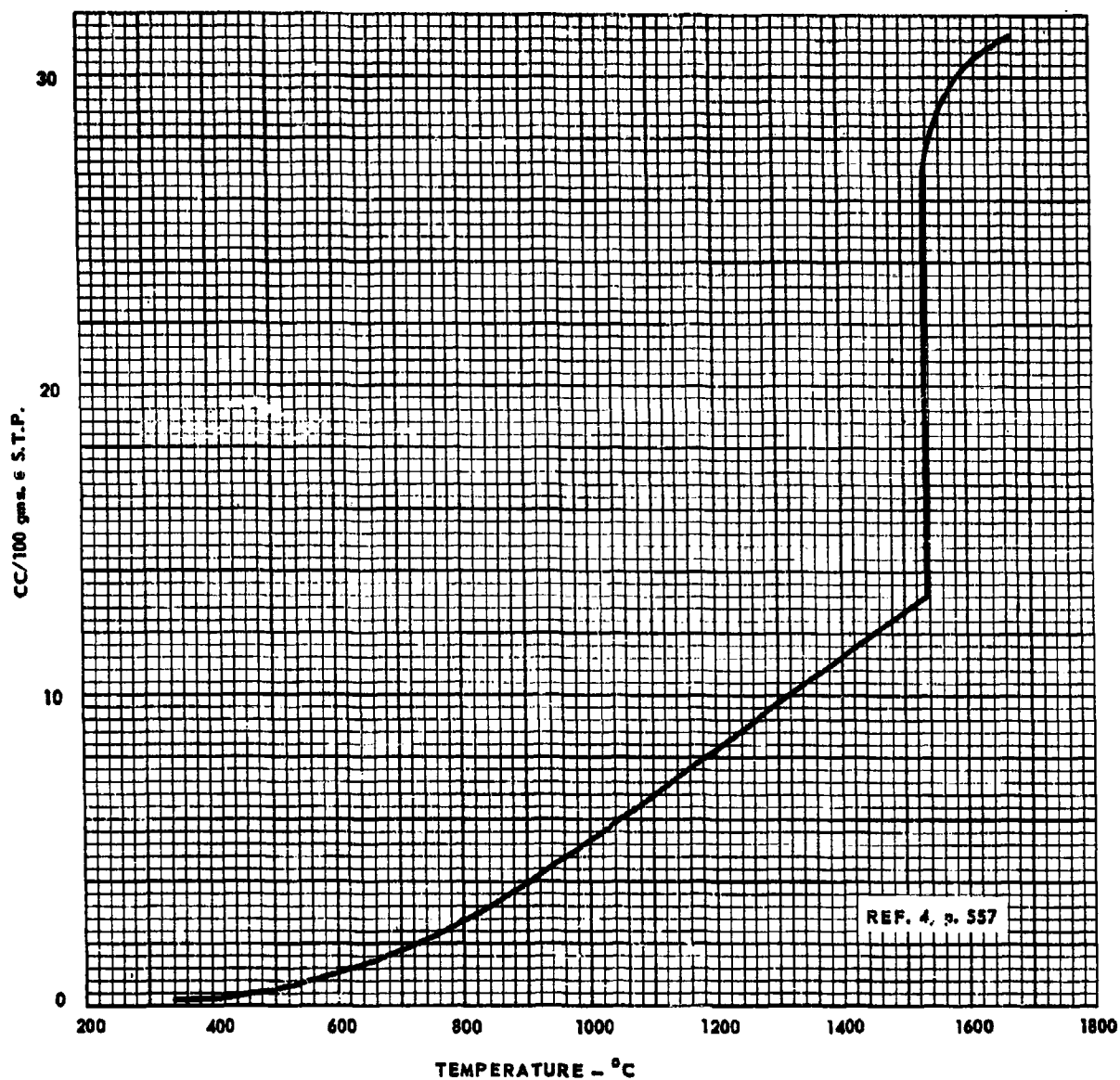


Fig. 32 — Hydrogen Solubility in Iron

Material: KovarChemical Composition: (Nominal %)

Nickel	- 29.0	Cobalt	- 17.0
Manganese	- 0.50 max.	Carbon	- 0.06 max.
Magnesium	- 0.10 max.	Titanium	- 0.10 max.
Silicon	- 0.20 max.	Aluminum	- 0.10 max.
Zirconium	- 0.10 max.	Al + Mg + Zr + Ti	- 0.20 max.
		Iron	- Remainder

Trade Designations: Kovar*, Fernico**, Rodar***, Therlo****

Suppliers: Carborundum Co., Latrobe, Penna.

General Electric Co., Schenectady, N. Y.

W. B. Driver Co., Newark, N. J.

Driver-Harris, Harrison, N. J.

Forms: Strip, sheet, wire, rod, tube, cups, eyelets

General:

Kovar and the other alloys mentioned above are used predominantly for glass-to-metal seals. Kovar was developed specifically for this application. It is a magnetic material, and when designing components for magnetrons, traveling-wave tubes, Klystrons, etc., the magnetic characteristics of the alloy must be kept in mind.

* Reg. T. M. Westinghouse Electric Corp.

** Reg. T. M. General Electric Co.

*** Reg. T. M. W. B. Driver Co.

**** Reg. T. M. Driver-Harris

Special Handling Techniques and Formability:

Forming properties of Kovar are somewhat better than those of mild steel; annealed sheet may be readily drawn. Spinning is more difficult because of the formation of minute circumferential (orange-peel) fractures which can cause vacuum leaks. If spinning is necessary, provision must be made for a tool radius of at least twice the thickness of the metal, the material must be annealed frequently, and critically examined over the areas of greatest strain.

Any mechanical working should be followed by annealing prior to brazing and glassing.

Kovar machines similar to Monel "R" (Machinability Index is about 45 on basis of B-1112 steel = 100); carbide or high-speed steel tools may be used.

Work speed of approximately 155 to 225 SFM with .005" feed and .010" depth-of-cut are also typical. Lard oil may be used as cutting fluid.

Joining:

Kovar may be attached to itself or other metals by mechanical fasteners (rivets, bolts), soldering, brazing, welding or glassing. For vacuum tube work the brazing, spot-welding, and glassing techniques are of general interest. Minimum time and current settings should be used for spot-welding .010" Kovar. Welds are easily made when parts are clean - no special atmosphere or cooling is needed.

Clean parts should be brazed without flux in dry hydrogen. Brazing with silver-bearing alloys is to be avoided especially with those alloys melting below 850°C . Intergranular penetration may result, especially if joint is not annealed and is to be reheated in further processing or use. Copper-plating helps limit the silver penetration, but best results are obtained by using annealed, strain-free Kovar at the joint and a brazing compound such as copper, gold, or gold-copper alloys, with or without some nickel additions. Furnace brazing above 950°C will anneal the joint while brazing.

To oxidize Kovar parts for glassing, the degreased metal is fired at 1000°C for 30 minutes in wet hydrogen, cooled in the furnace, and carefully protected from dirt, dust, and grease until the glassing operation. If possible, the glassing should take place within one or two hours after the oxidation process.

Allotropic Changes:

Kovar may be safely heated to 1050° - 1100°C in dry hydrogen for periods up to one hour without excessive grain growth. The transformation temperature from gamma to alpha phase is below -80°C .

Ease of Outgassing:

Kovar outgasses readily in vacuum at 800° - 900°C after firing in dry hydrogen 10 to 20 minutes at 1100°C .

Applications:

Typical applications are for glass and ceramic seals, feed-through connectors, vacuum envelopes, etc.

KOVAR

Table 11
KOVAR DATA

		<u>Ref.</u>
Density	8.36 g/cc	1, p. 184
Melting Temp.	1450°C	53
Modulus of Elasticity	20 x 10 ⁶ psi	2
Thermal Conductivity	0.0395 cal/sec/cm/°C at 30°C 0.0485 cal/sec/cm/°C at 300°C	53 53
Specific Heat	0.105 cal/g/°C at 0°C 0.155 cal/g/°C at 430°C	53 53
Curie Point	435°C	53
Magnetic Permeability	3700 max. at 7000 gauss	53
Linear Thermal Expansion	6.19 in/in/°C, 30 to 500°C	53
Electrical Resistivity	49 x 10 ⁻⁶ ohm-cm (25°C)	53
Tensile Strength	77,500 Psi (21°C)	53
Yield Strength	59,500 Psi (21°C)	53
Maximum Elongation	35.4%	
Temp. for 10 ⁻⁵ Vapor Pressure	1175°C	73

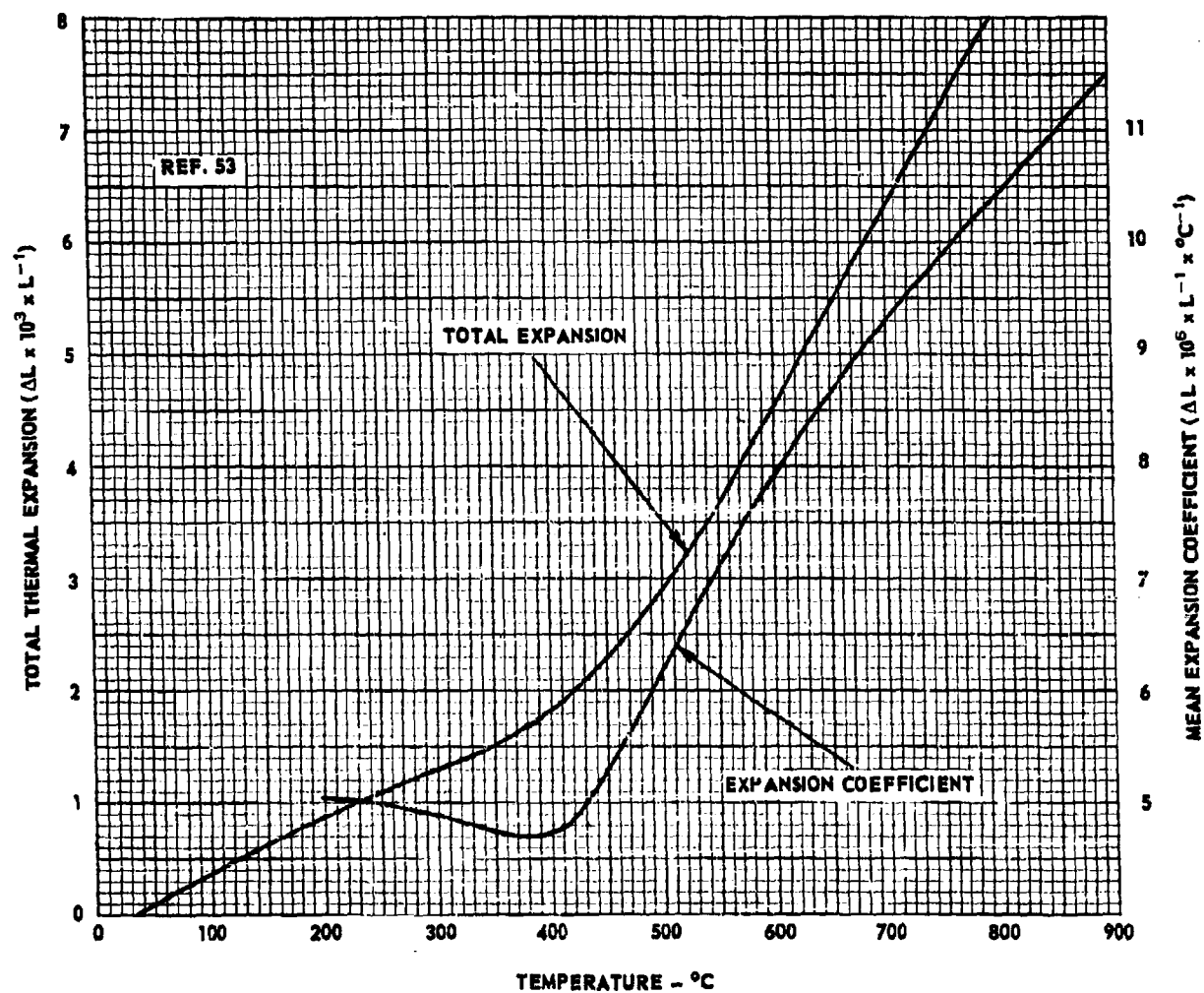


Fig. 33 — Linear Thermal Expansion and Coefficient of Expansion for Kovar.

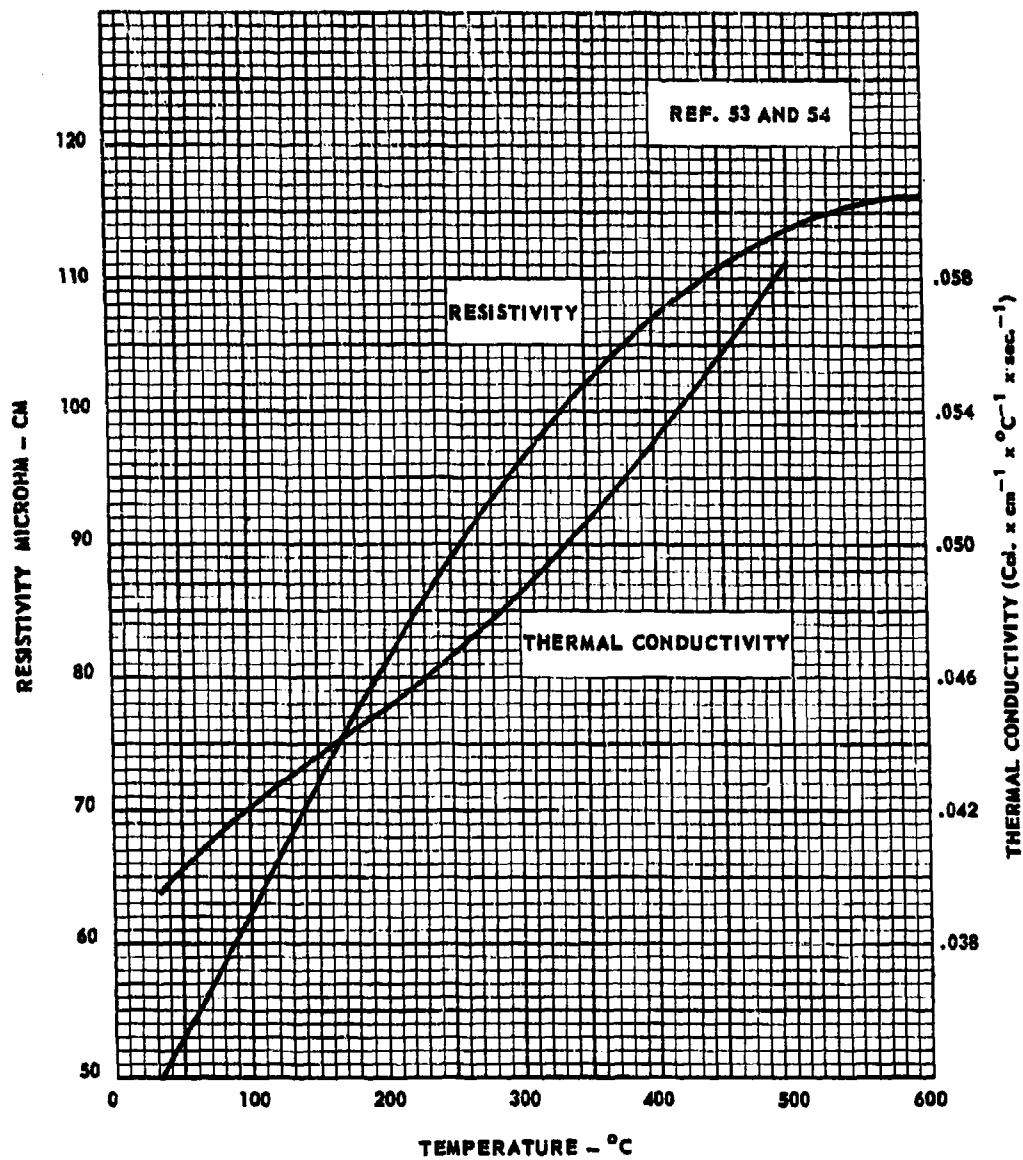


Fig. 34 — Electrical Resistivity and Thermal Conductivity of Kovar

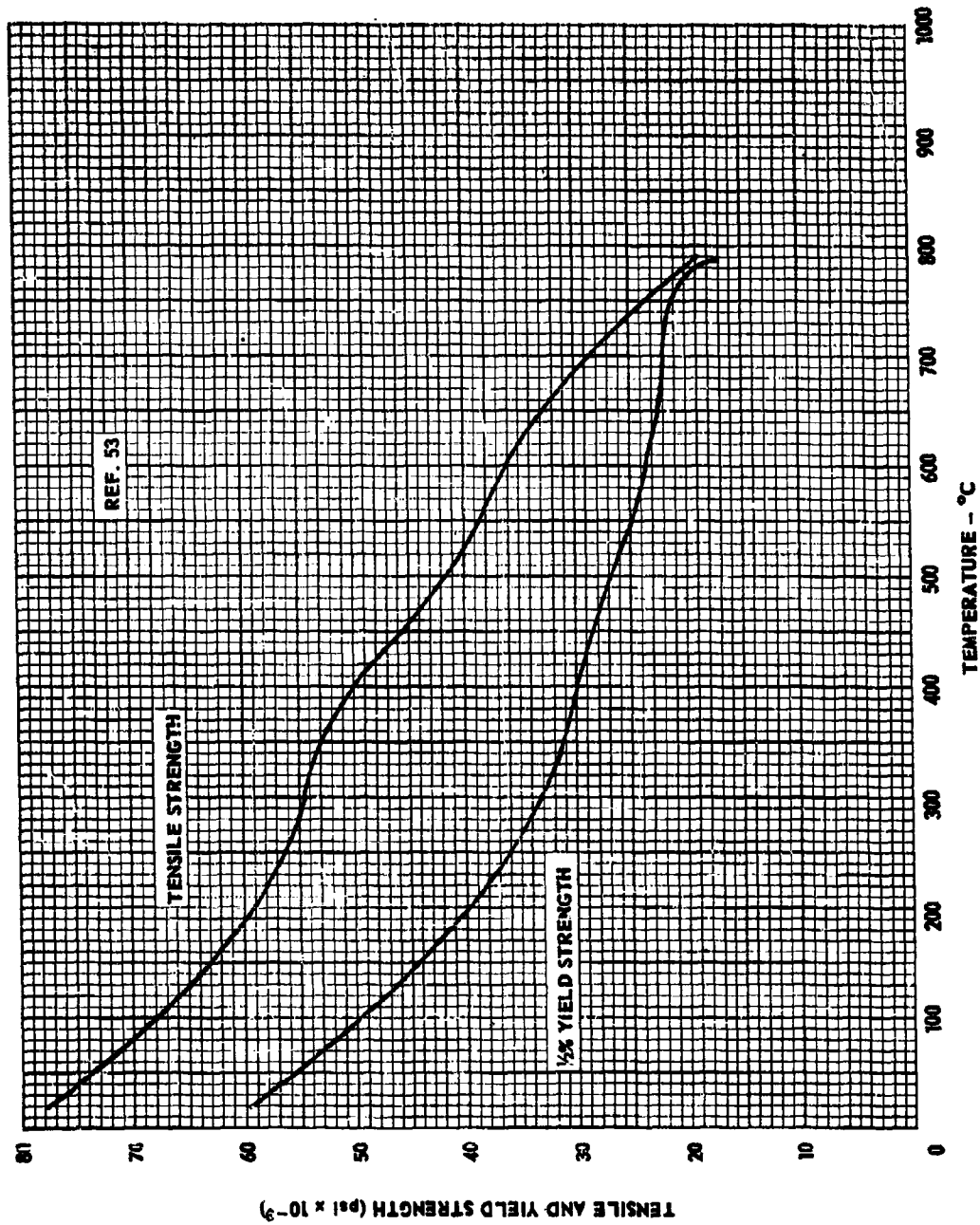


Fig. 35 — Tensile Strength and Yield Strength of Kovar

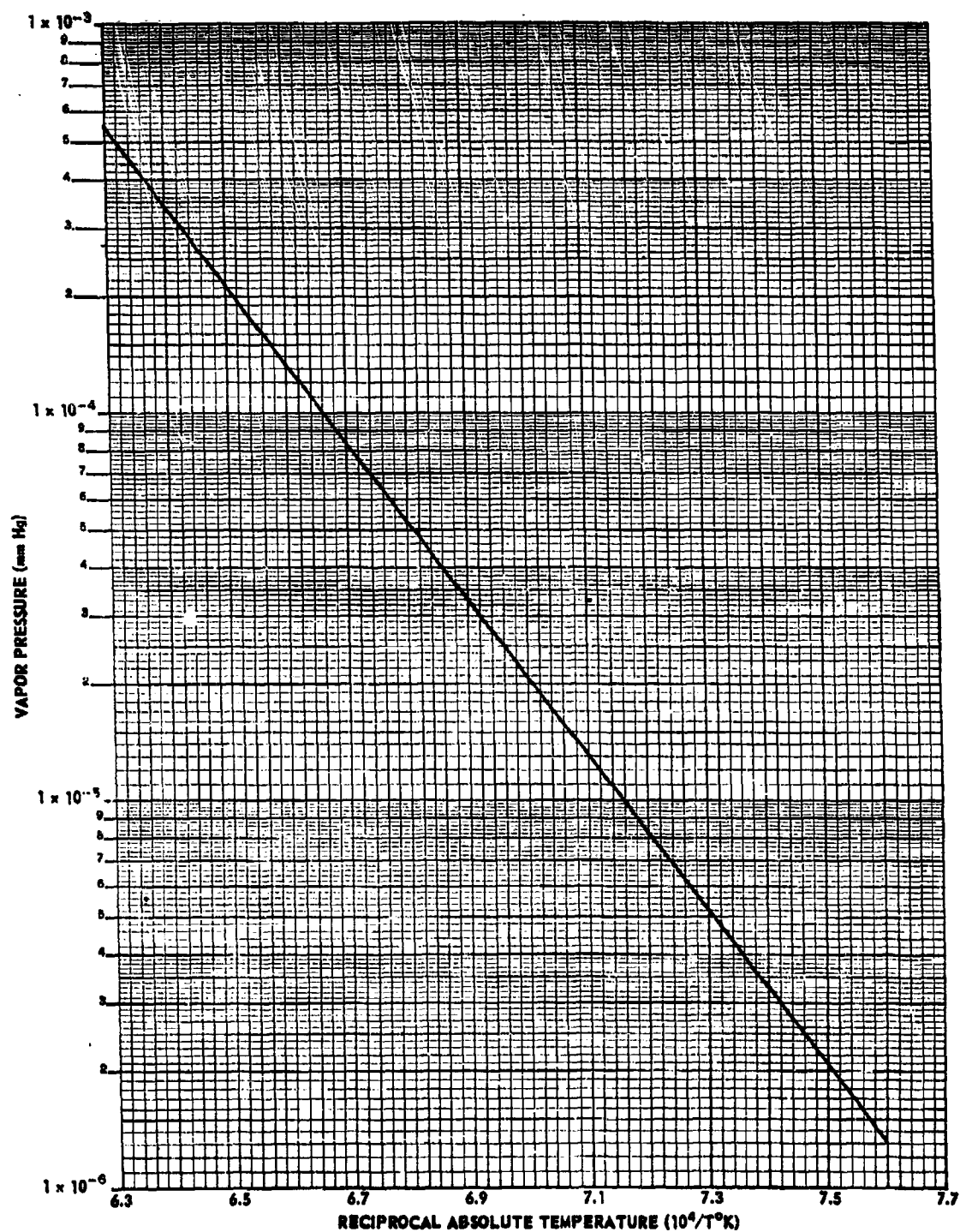


Fig. 36 — Vapor Pressure of Kovar

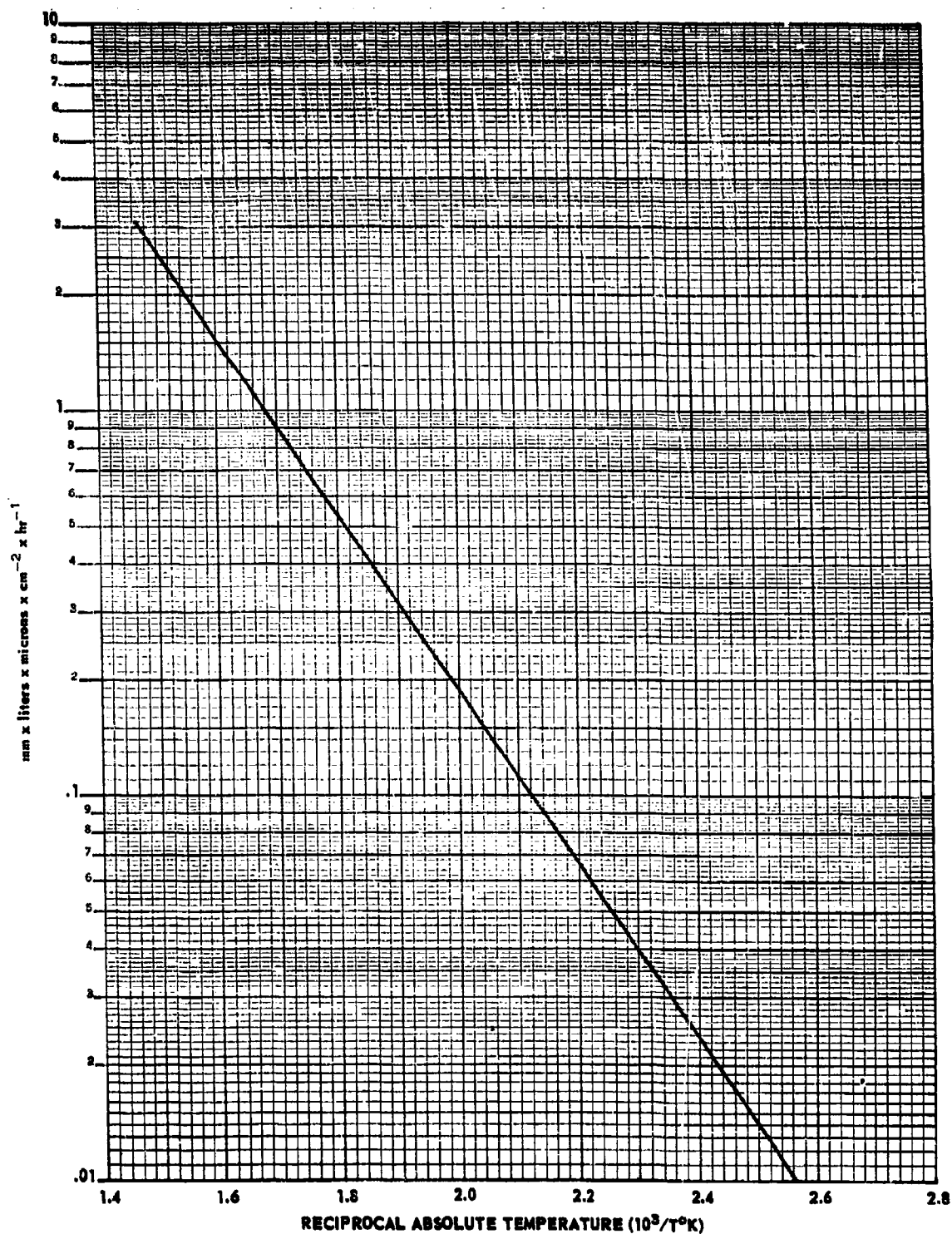


Fig. 37 — Hydrogen Permeation Through Kovar

MOLYBDENUM

Material: Molybdenum

Chemical Composition: 99%+ Molybdenum

Suppliers: Climax Molybdenum Co., 500 Fifth Ave., New York 36, N. Y.

Wah Chang Corp., 233 Broadway, New York 7, N. Y.

Fansteel Metallurgical Corp., North Chicago, Illinois

North American Phillips, Lewiston, Maine

Forms Available: Powder, bar, rod, sheet, wire, tube

General:

Molybdenum, one of the best known and most commonly used of the refractory metals, is a member of Group VI of the periodic table, with atomic number 42. Its melting point, 2625°C (4757°F), is exceeded by those of only four other elements: tantalum, rhenium, tungsten, and carbon. Its vapor pressure is low, approximately that of carbon. It is a mechanically strong metal; its electrical conductivity is one-third that of copper. Chemically it exhibits valences from two to six; in the lower valence states it is basic, and in the higher states it is acidic.

Special Handling Techniques and Formability:

The following is an excerpt from a publication of the Climax Molybdenum Company, "Arc-Cast Molybdenum and Its Alloys", 1955:

"The mechanical properties of unalloyed molybdenum and the four alloys commercial today depend to a large degree on the amount of working done below the recrystallization temperature (so-called warm working). For optimum ductility, parts should be given at least a 50 percent reduction in area by warm working.

Full recrystallization gives lower strengths than do other prior treatments, so fully recrystallized molybdenum flows more easily in working.

It does, however, have very poor bending properties although the tensile elongation is higher than in other conditions. Therefore, full recrystallized molybdenum is used for the fabrication of parts only if no bending or deep drawing is to be done; or if mechanical properties after working are not important; or if subsequent processing will involve sufficient warm work to produce the necessary properties. . . .

The toughness and ductility of molybdenum are not very high at room temperature although they increase markedly at temperatures somewhat above room temperature (for example 400°F). Therefore, except for fine wire and sheet, at least a moderate amount of heating is recommended for all working operations.

Because of its high thermal conductivity and low specific heat, molybdenum heats and cools much more rapidly than steel.

Molybdenum and its alloys have unusually high strength at elevated temperatures. Therefore, for a given amount of work, more powerful presses and hammers are needed than for any of the other common metals."

At temperatures above 250°C, graphite lubricant may be used with forming tools of hot work alloy steel or tungsten carbide. Machining characteristics are similar to those of cast iron.

Allotropic Changes and Crystal Growth:

Molybdenum does not undergo any allotropic transformations on heating and cooling. Crystal growth begins at about 900°C, causing embrittlement if carried too far.

There is no appreciable size change on heating and cooling. although unsupported parts fabricated from wire may change position somewhat when stress-relieved.

MOLYBDENUM

Ease of Outgassing:

Molybdenum outgasses quite readily in vacuum or dry hydrogen at about 1000° to 1100°C.

Joining:

Molybdenum may be joined to itself or other metals by riveting, brazing, or spot-welding. Molybdenum rivets may be used (work while hot!), or softer metals may be substituted. Brazing is usually done in dry hydrogen without flux (use clean parts); silver, copper, nickel, or proprietary alloys are used.

Spot-welding is more effective if a projection type weld is made. Sometimes a piece of nickel or tantalum foil is placed between parts to be welded; oxidation can be minimized by welding under water or carbon tetrachloride.

For welding molybdenum to itself when part thickness exceeds .025", we may use an inert gas arc weld without filler.

Applications:

Molybdenum is used for grids, anodes, cathode assemblies, and other structures which are subjected to high stress at elevated temperatures in vacuum. The superior formability and cost differential with respect to tungsten, and the excellent high-temperature properties as compared to the commoner metals will usually delineate the proper fields of application for molybdenum.

MOLYBDENUM

Table 12
MOLYBDENUM DATA

		<u>Ref.</u>
Density	10.2 g/cc	5, p. 626
Lattice Type	Body-centered cubic	8, p. 122
Melting Temperature	2622°C	5, p. 626
Annealing Temperature	1000°C	5
Tensile Strength	90,000 Psi (annealed) 120,000 Psi (Unannealed)	5
Yield Strength	56,000 Psi	37
Modulus of Elasticity	50 x 10 ⁶ Psi	5, p. 637
Maximum Elongation	15%	5
Thermal Conductivity	0.35 cal/cm/°C/sec.	2
Specific Heat	0.0624 cal/g at 20°C 6.24 cal/g-atom at 20°C	5, p. 627 5, p. 278
Linear Thermal Expansion	6.0 x 10 ⁻⁶ /°C (25 - 700°C)	1, p. 84
Spectral Emissivity	0.37	21
Electrical Resistivity	5.7 x 10 ⁻⁶ ohm-cm	17, p. 50
Temp. Coefficient of Resistivity	47 x 10 ⁻⁴ /°C	5
Magnetic Susceptibility	0.04 x 10 ⁻⁶	7, p. 688
Electron Work Function	4.37 eV	8, p. 122
Positive Ion Emission	8.6 eV	5, p. 278
Secondary Electron Emission	δ max. = 1.25; V at δ max. = 375	17, p. 89
Temp. for 1 x 10 ⁻⁵ Vapor Pressure	1987°C	81
Outgassing Temp. in Vacuum	950°C	8, p. 36

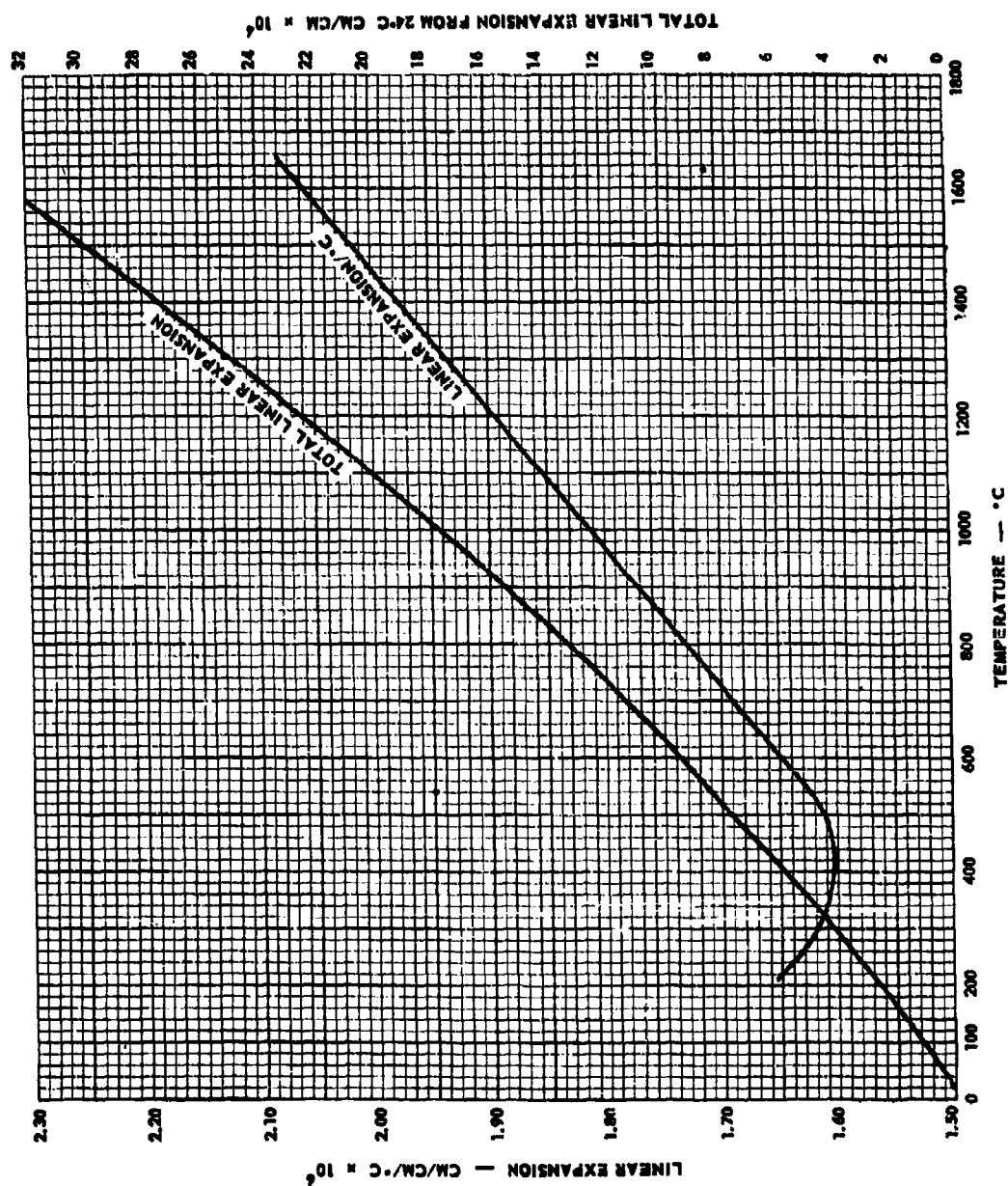


Fig. 38 — Linear Thermal Expansion and Coefficient of Expansion
for Molybdenum

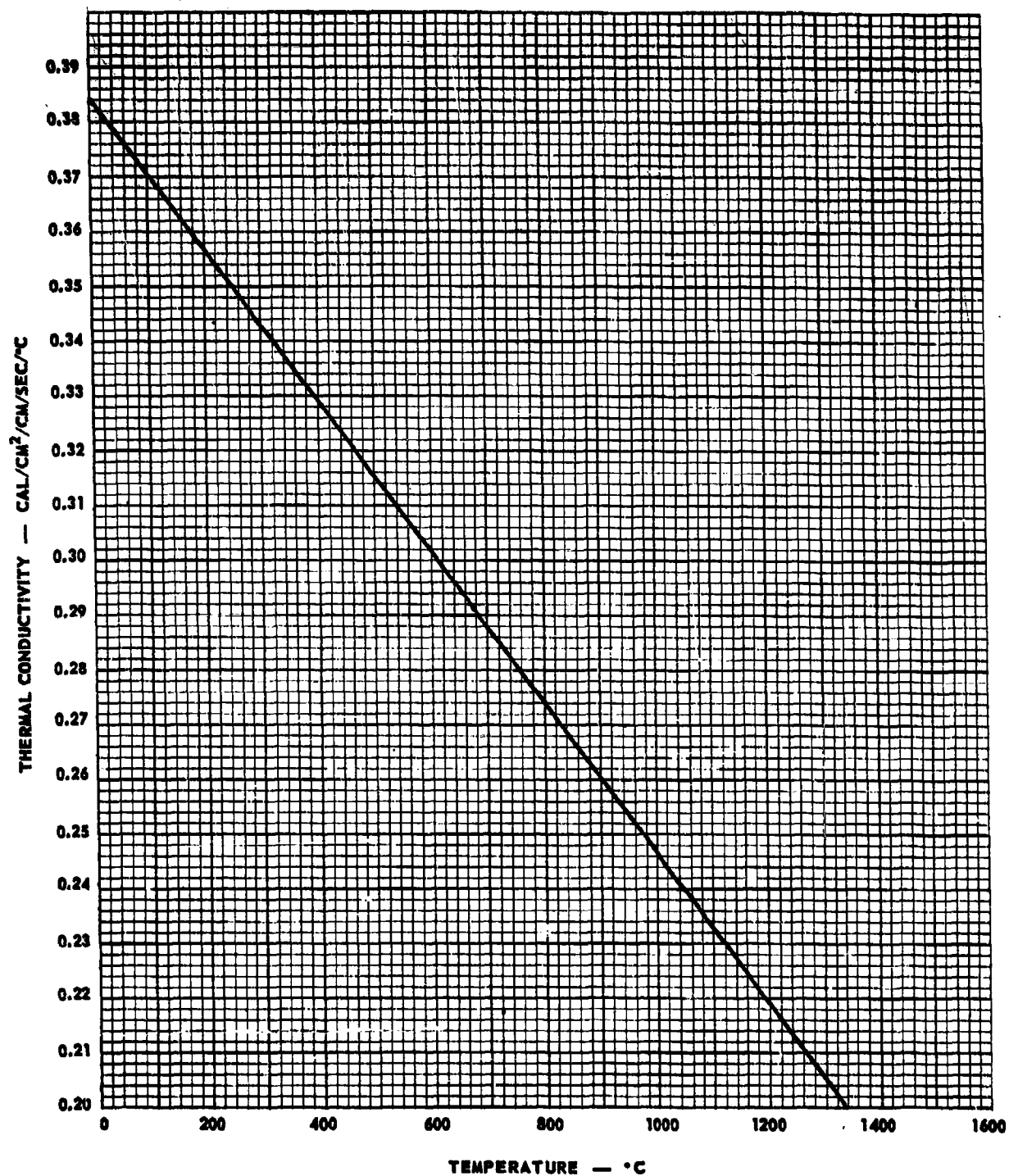


Fig. 39 — Thermal Conductivity of Molybdenum

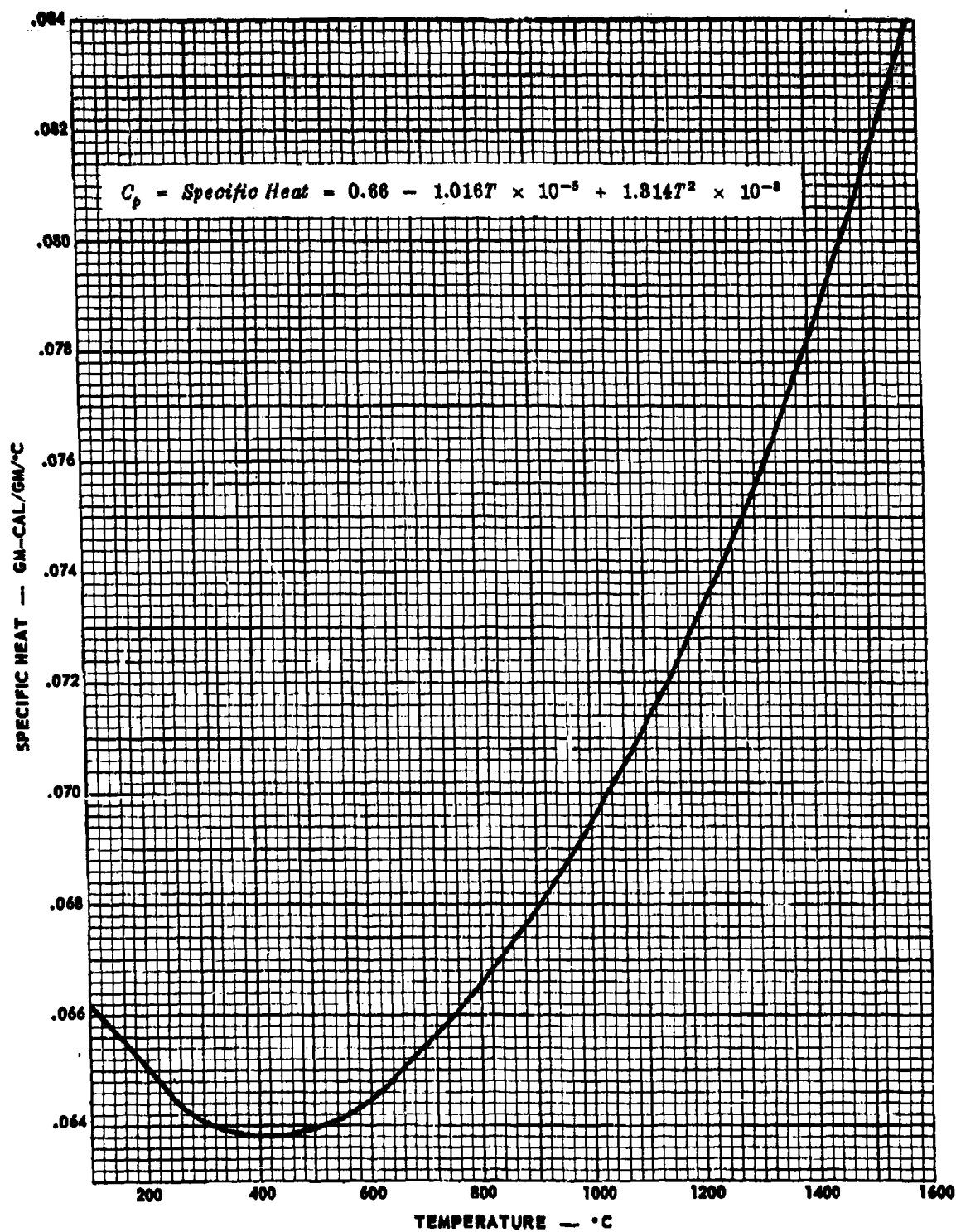


Fig. 40 — Specific Heat of Molybdenum

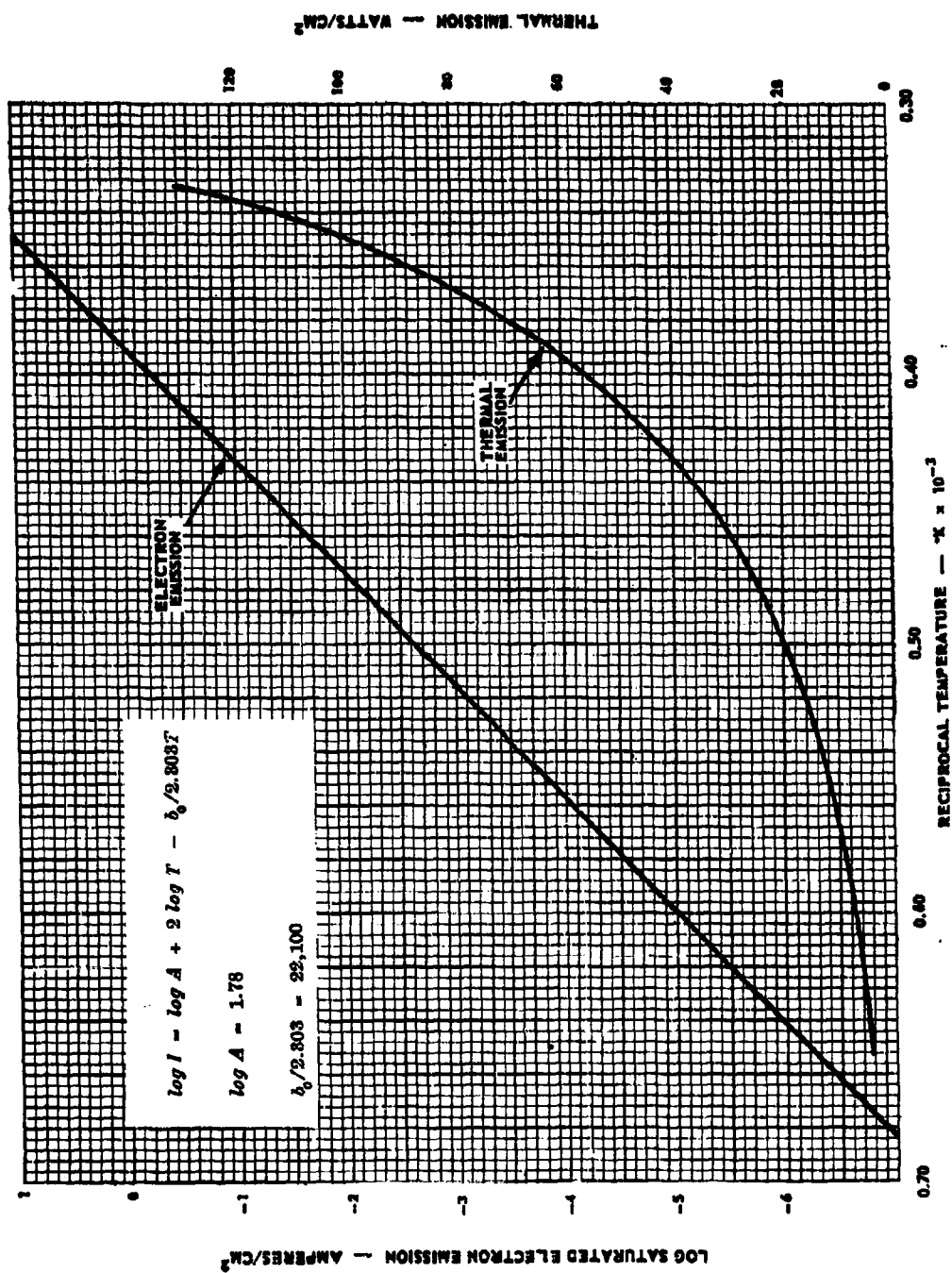


Fig. 41 — Thermionic Emission and Thermal Emission of Molybdenum

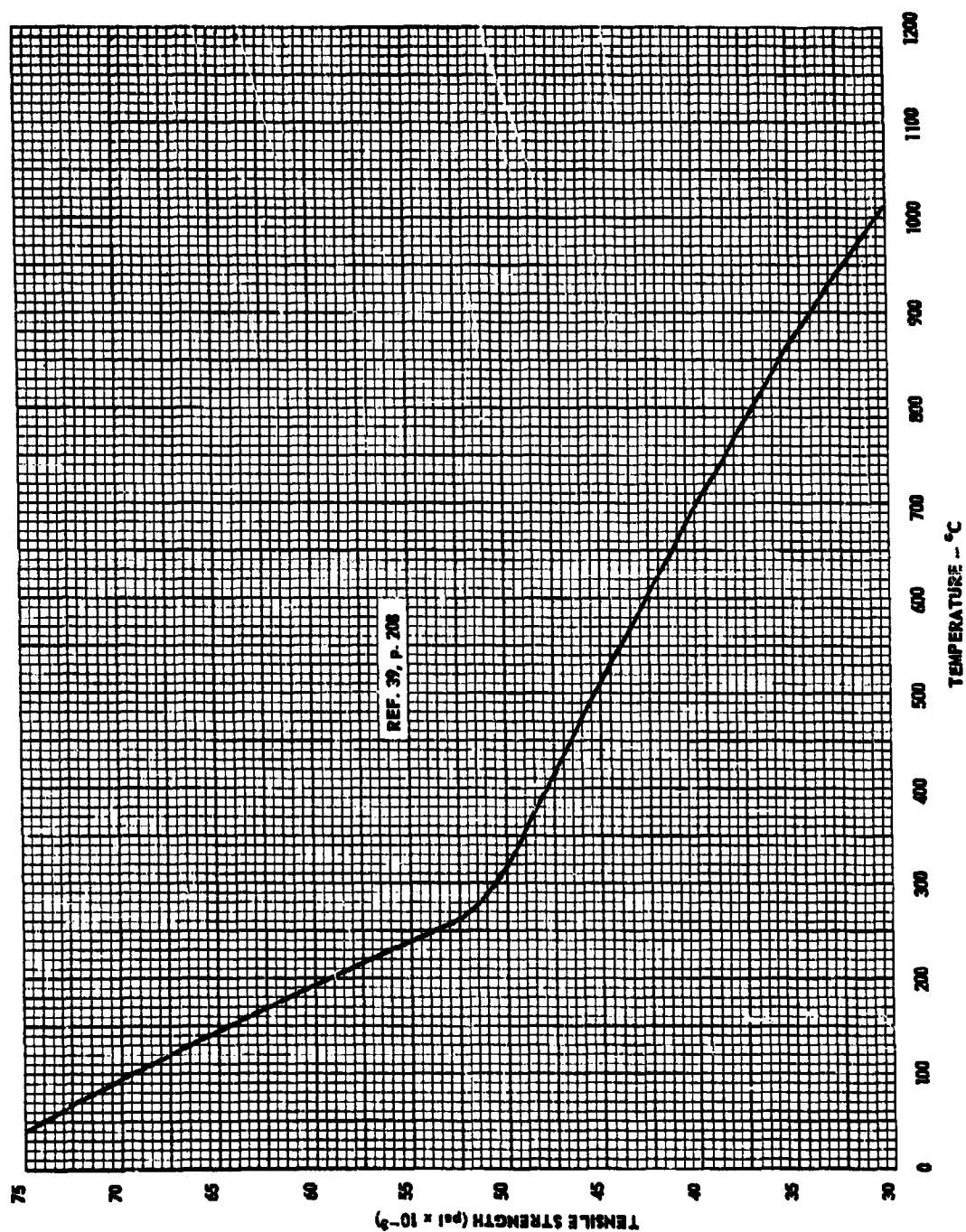


Fig. 42 — Tensile Strength of Molybdenum

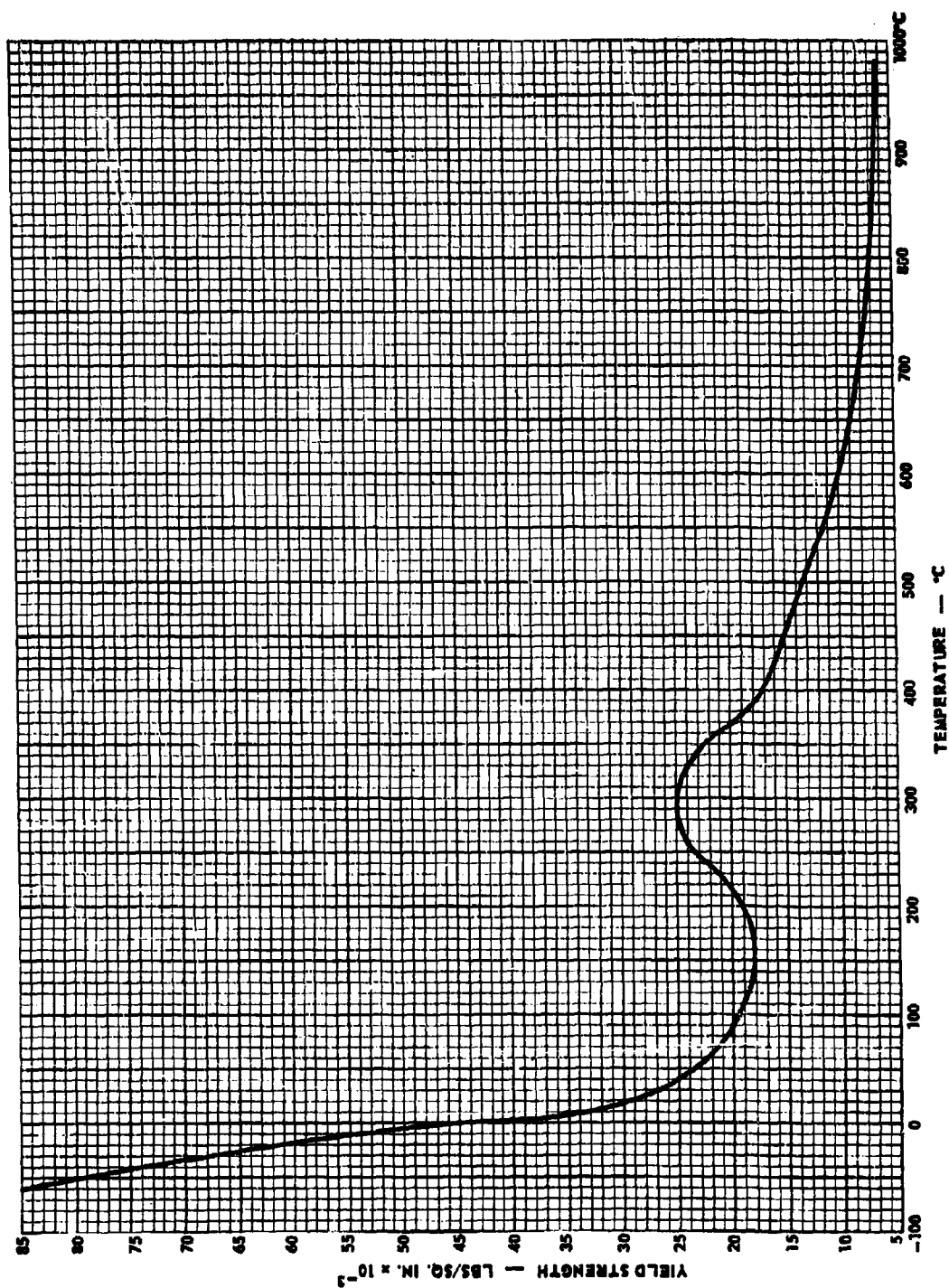


Fig. 43 -- Yield Strength of Molybdenum

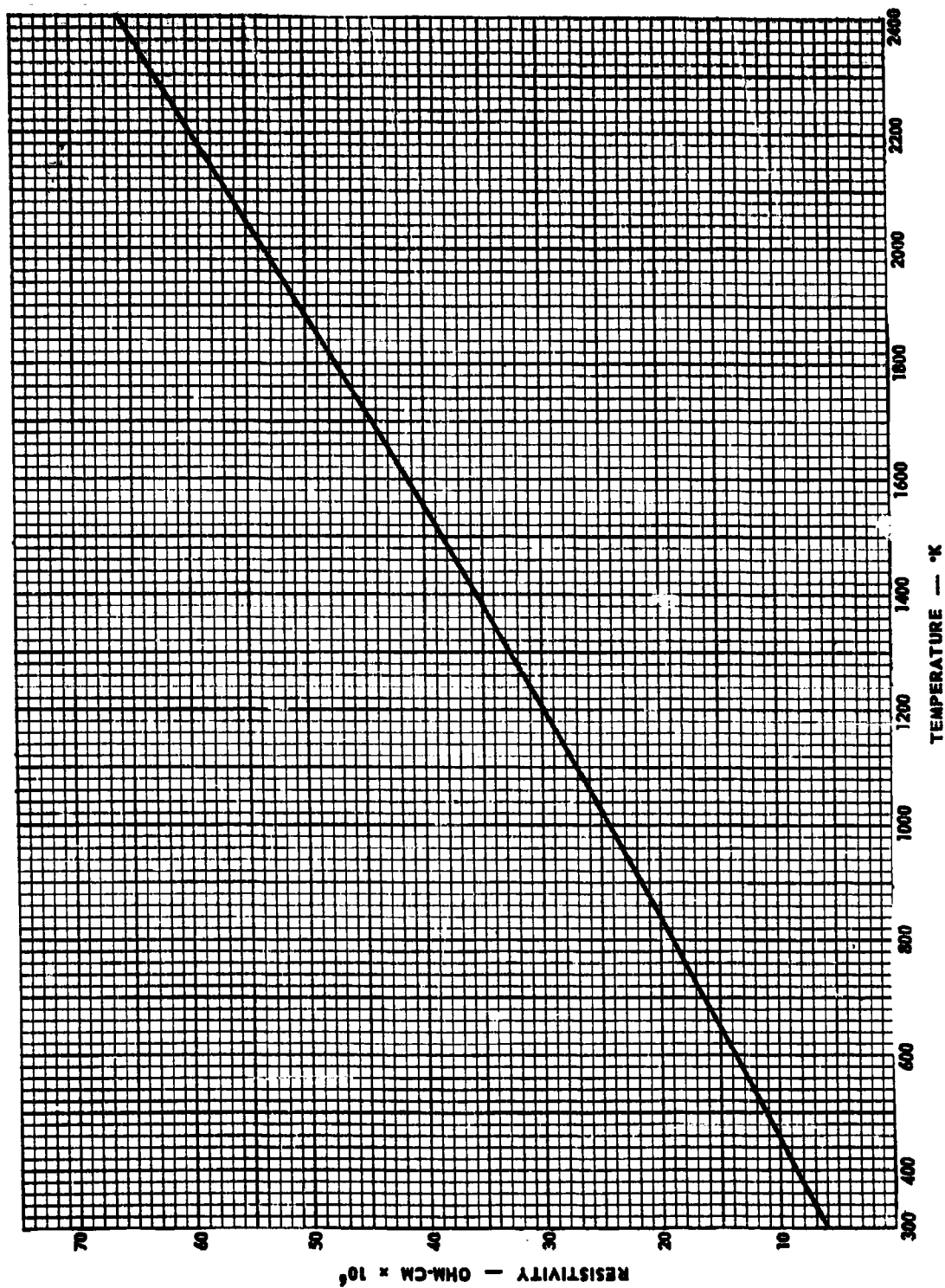


Fig. 44 — Electrical Resistivity of Molybdenum

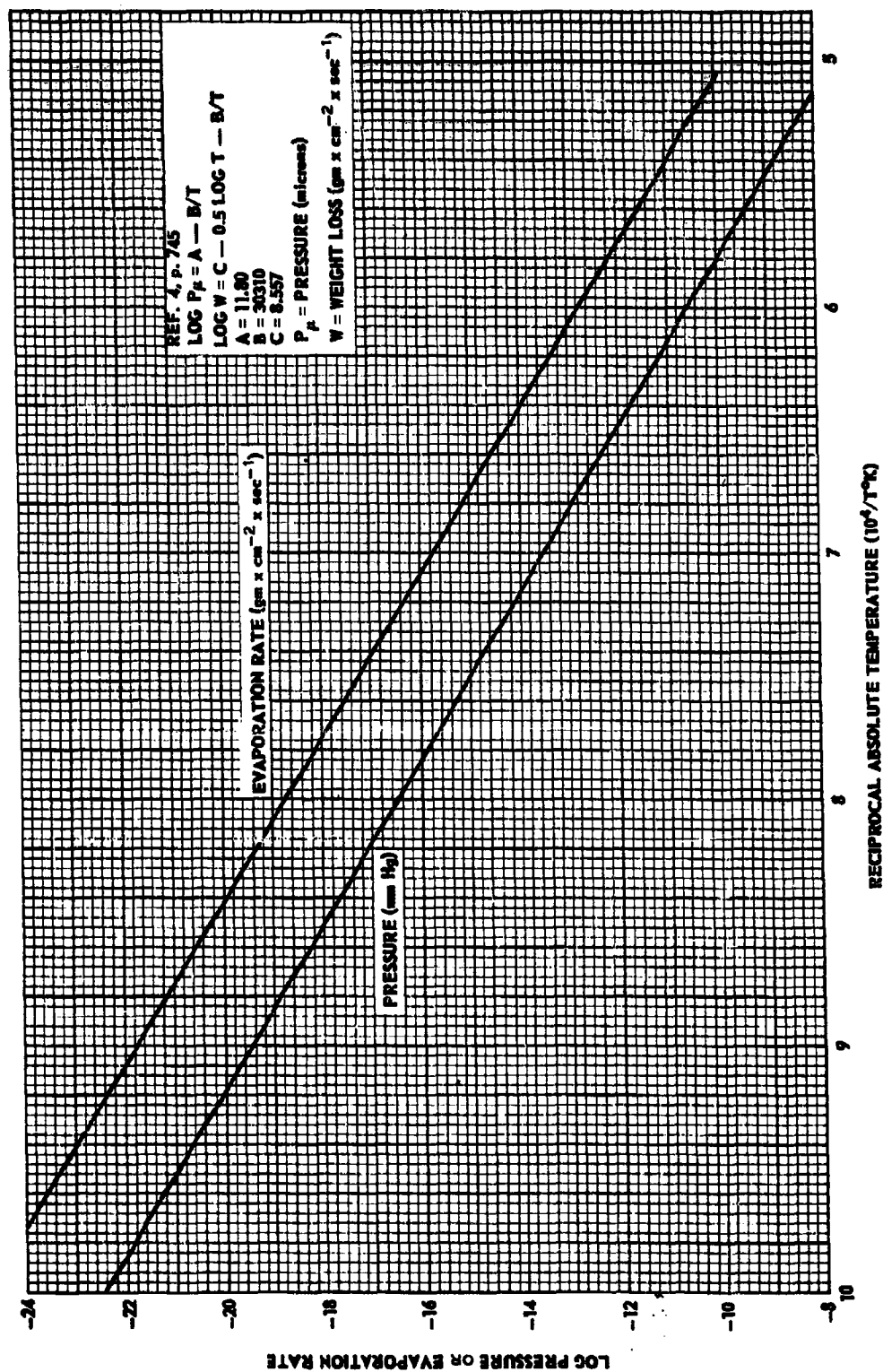


Fig. 45 — Vapor Pressure and Evaporation Rate of Molybdenum

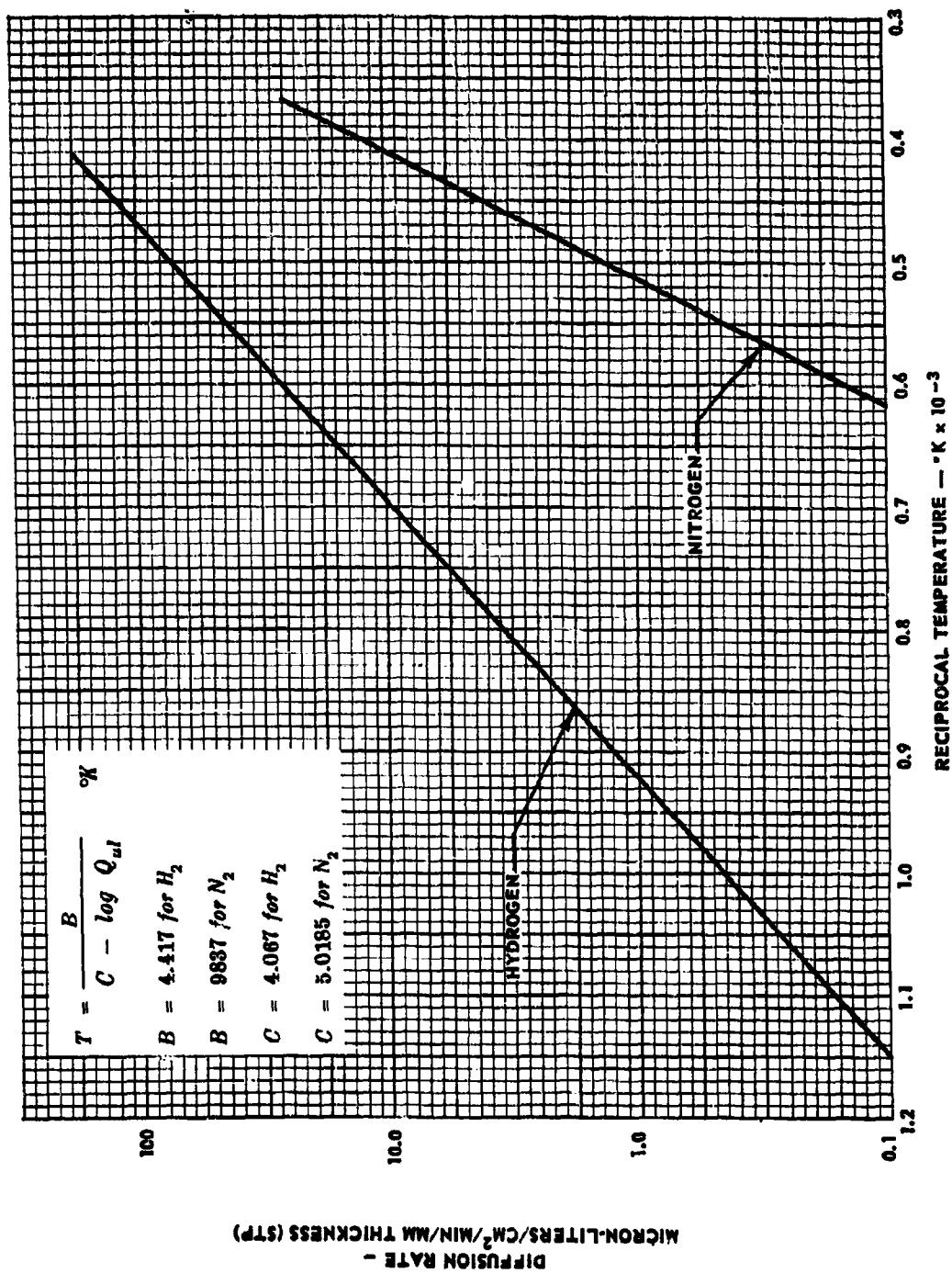


Fig. 46 — Hydrogen and Nitrogen Permeation Through Molybdenum

Material: Monel "403"

Chemical Composition:

	<u>Limits (%)</u>	<u>Nominal (%)</u>	
Carbon	0.30 Max.	0.12	Ref. 22, p. 3
Manganese	1.25 to 2.25	1.80	
Iron	1.00 Max.	0.50	
Sulfur	0.024 Max.	0.005	
Silicon	0.75 Max.		
Nickel and Cobalt	55.0 to 60.0	57.5	
Copper	Remainder	39.8	

Trade Designations: Monel "403" *

Suppliers: International Nickel Co., 67 Wall St., New York 5, N.Y.

Forms Available: Plate, sheet, strip, rod, bar, wire, pipe, tube

General:

Monel "403" is a low permeability alloy used for applications requiring comparatively high strength and resistance to corrosion, especially where low magnetic permeability is desired. It is useful in the electronic industry because it is relatively easy to machine and form and can be welded or brazed using normal shop practices. The room temperature permeability is usually of the order of 1.004 at a field strength of 200 oersteds. The maximum will not exceed a value of 1.1 even for parts which have not been annealed after forming.

*T. M. Reg. - Int. Nickel Co.

Joining:

Monel "403" may be copper or silver-brazed to itself or to other common electron tube materials. Since the coefficient of expansion of this alloy is very close to those of stainless steel and copper, composite structures made of these materials are relatively stable to thermal cycling. The preferred method for joining thin parts is spot-welding. Brazing filler alloys used with Monel "403" must be free of phosphorus.

Special Handling Techniques and Formability:

This alloy may be drawn, spun or blanked, using techniques similar to those for handling soft steel. For blanking and punching, soft to quarter-hard stock is used with punch and die clearances the same as or slightly less than for steel. In drawing and spinning well-annealed material free from scratches and surface imperfections is used, allowing generous radii on all edges and corners. Tools should be polished and well lubricated; a sulfurized, fatty mineral oil may be used as a lubricant but must be completely removed before any further heat treatment. For electron tube applications it is best to avoid the use of sulfur bearing oils entirely to assure freedom of sulfur contamination in the tube. In drawing there is some tendency to gall with carbon steel dies. A 12% chromium air-hardening steel or a hard bronze alloy makes a better drawing tool than carbon steel. Monel "403", like other high-nickel alloys, is very sensitive to traces of sulfur, phosphorus, lead and carbon. Lubricating compounds, furnace atmospheres, and brazing alloys must be chosen with care and lead or sulfur-bearing materials must be completely removed from surfaces prior to heat treatment of any sort.

Allotropic Changes:

There are no changes in crystal form on heating and cooling. Grain growth is not particularly troublesome.

Ease of Outgassing:

Parts made of Monel "403" may be annealed for five to ten minutes at 870°C or one to four minutes at 980°C. If this annealing operation is performed in dry hydrogen, thin-walled components will outgas readily at about 900°C on the pump.

Applications:

The monels have been used in electron tubes for anodes, grids and supports. In microwave tubes or high power electron devices, monel is not recommended for anode or grid material because of its vapor pressure. In microwave tubes it is used as internal and external support structures and bellows in tunable tubes.

MONEL "403"

Table 13
MONEL "403" DATA

		<u>Ref.</u>
Density	8.858 g/cc	22, p. 6
Lattice Type	Face-centered cubic	13, p. 62
Melting Range	1300 - 1350°C	
Young's Modulus	25.2×10^6 Psi	22, p. 6
Thermal Conductivity	0.060 cal/cm/°C/sec at 20°C	
Specific Heat	0.100 cal/g/°C (at 20°C)	22, p. 6
Magnetic Permeability	1.004 (25°C), 200 oersted	22, p. 3
Electrical Resistivity	53×10^{-6} ohms - cm at 20°C	22, p. 6
Electrical Conductivity	3% IACS	
Mean Thermal Coefficient of Expansion	16.1×10^{-6} cm/cm/°C (20 - 600°C)	22, p. 6
Temp. for 10^{-5} mm Vapor Pressure	975°C	62, p. 30
Tensile Strength	65,000 Psi	22
Yield Strength	23,000 Psi	22
Maximum Elongation	50%	22

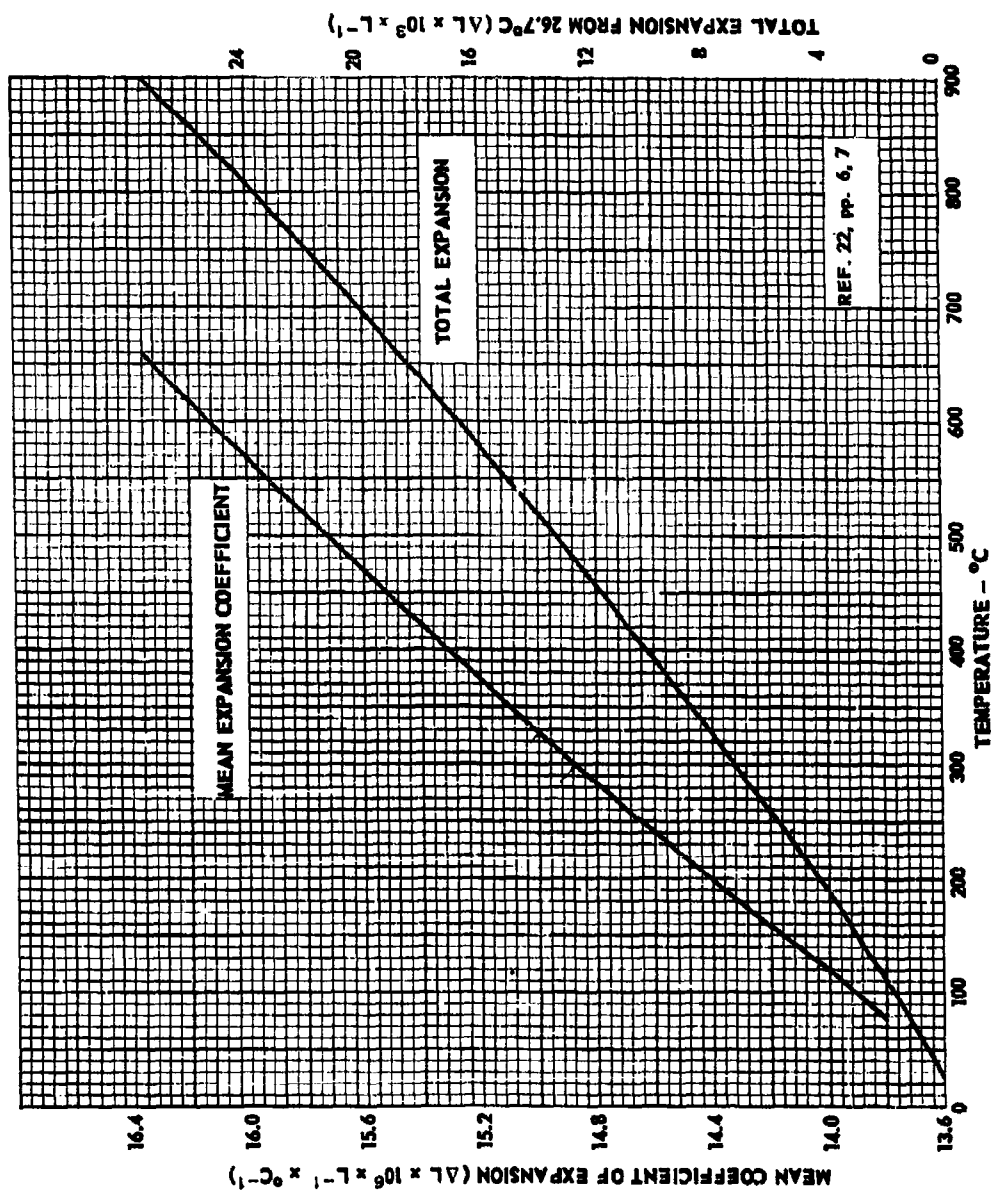


Fig. 47 -- Linear Thermal Expansion and Mean Coefficient of Expansion of Monel 403

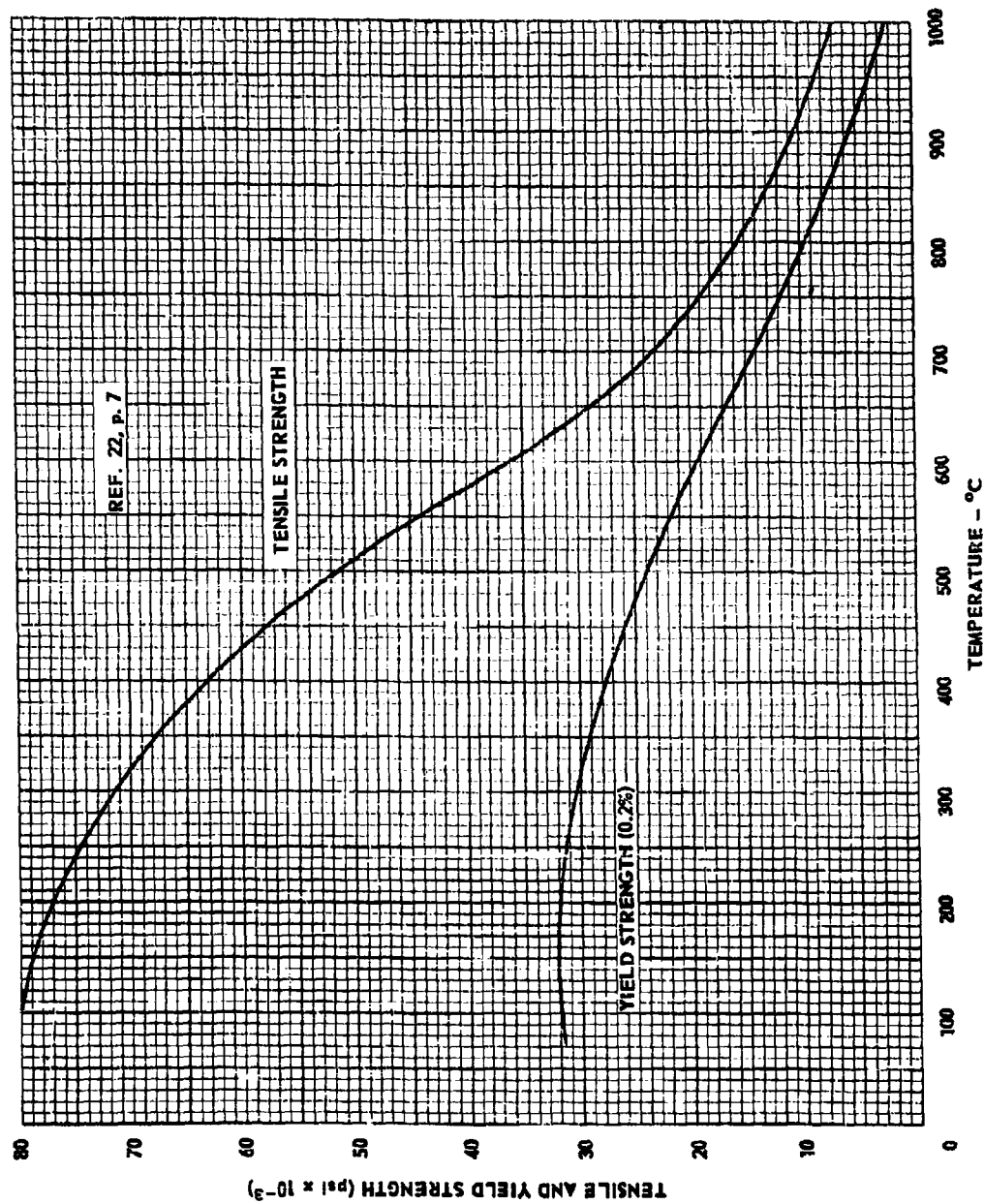


Fig. 48 -- Tensile Strength and Yield Strength of Monel 403

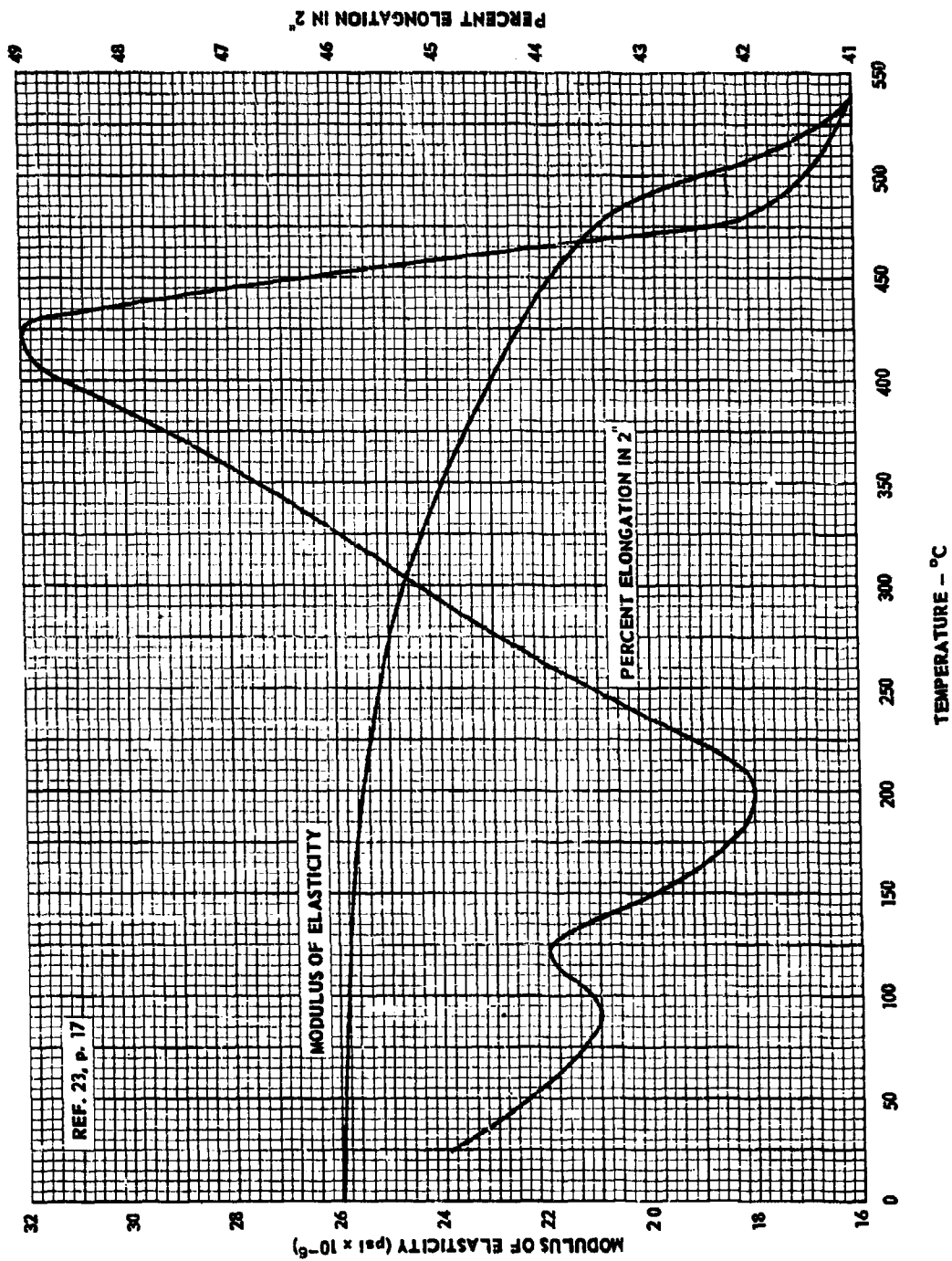


Fig. 49 — Modulus of Elasticity and Percent Elongation for Monel 403

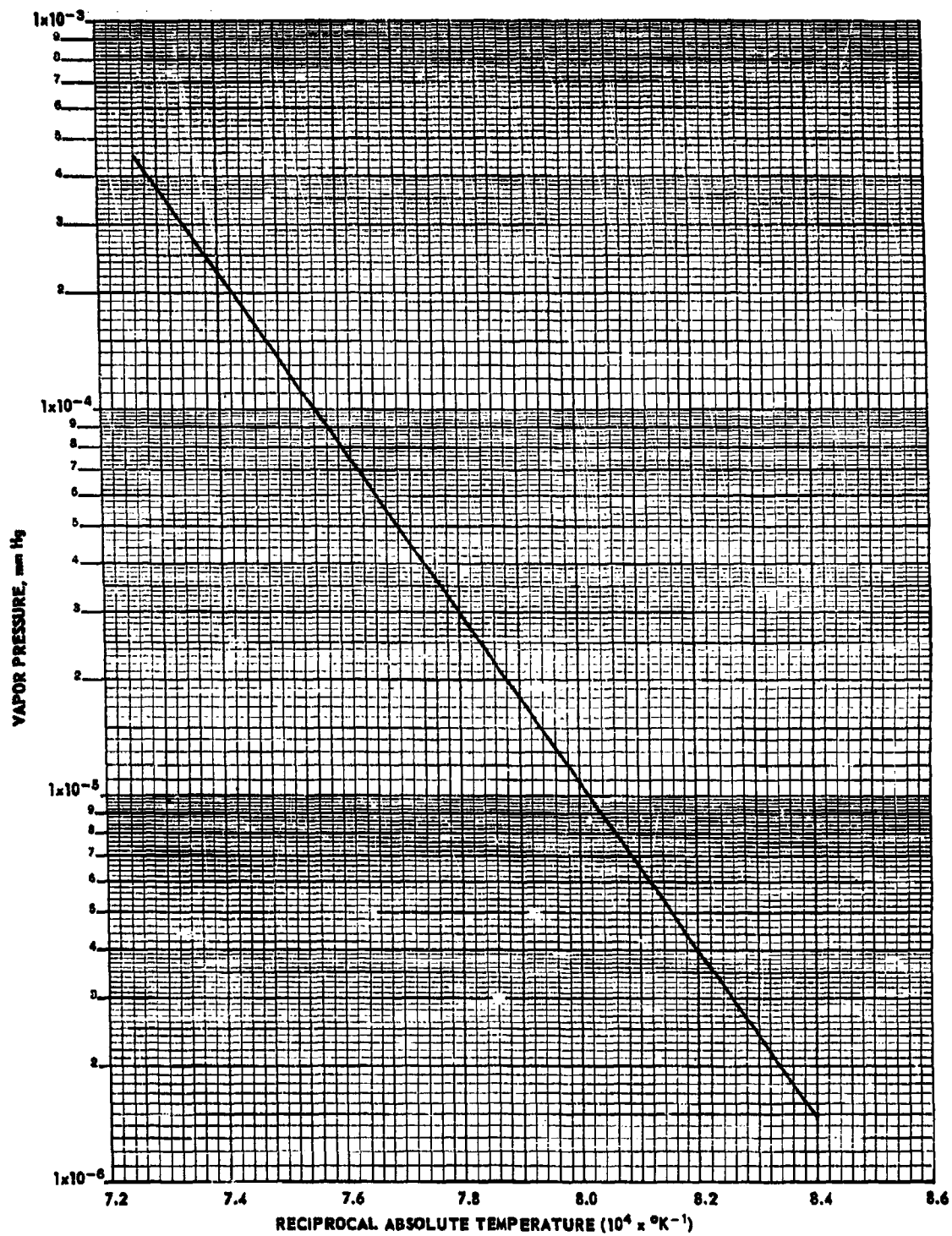


Fig. 50 — Vapor Pressure of Monel 403

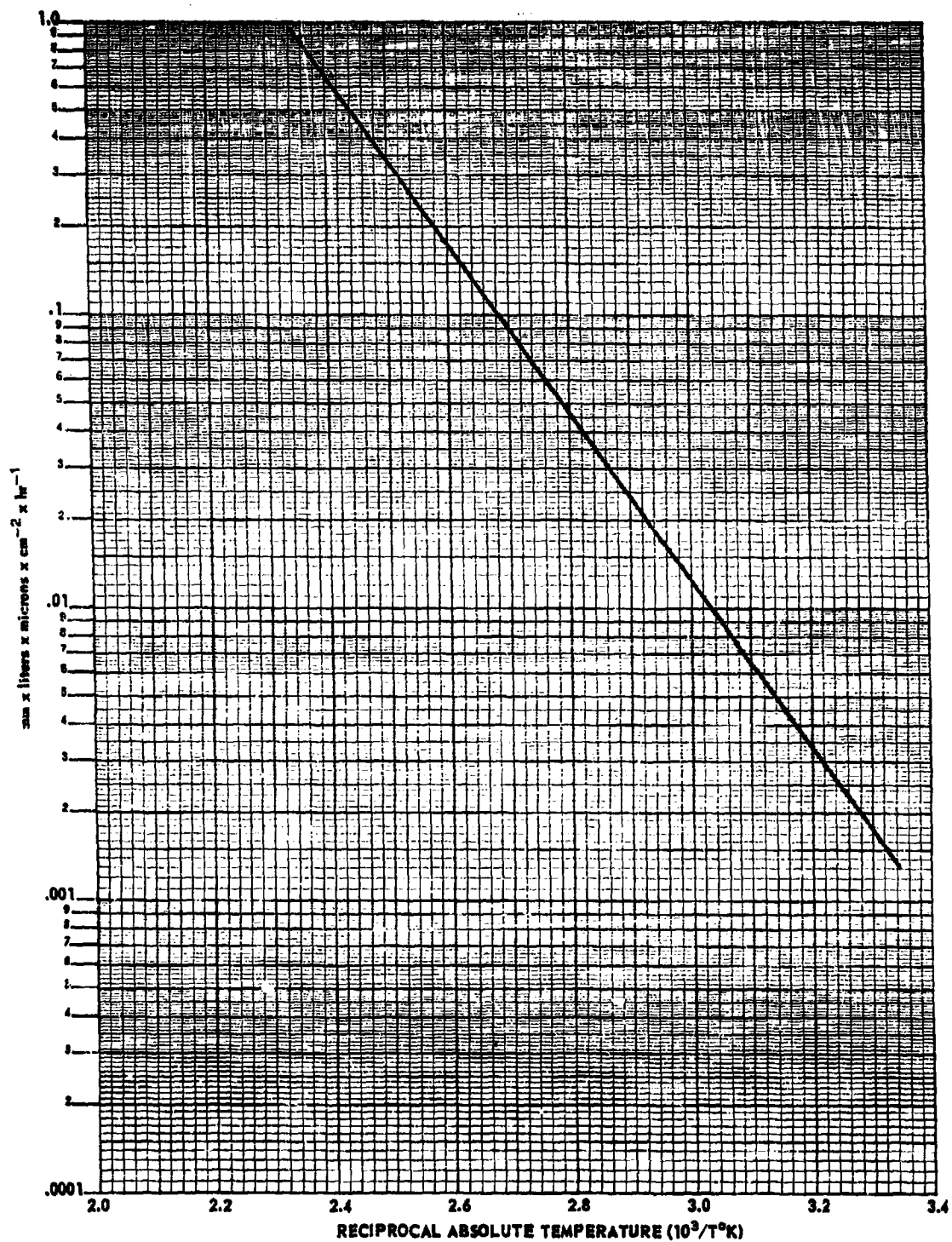


Fig. 51 — Hydrogen Permeation Through Monel 403

Material: Nichrome V

Chemical Composition(%): Nickel - 77 to 79 Carbon - 0.25 Maximum
 Manganese - 2.5 Maximum Iron - 1.0 Maximum
 Sulfur - 0.03 Maximum Silicon - 0.75 to 1.5
 Chromium - 19 to 20

Trade Designations: 80 Ni - 20 Cr

Nichrome V *

Tophet A **

Chromel A ***

Suppliers: Driver Harris Co., Harrison, N.J.

W. B. Driver Co., Newark, N.J.

Hoskins Manufacturing Co., Detroit, Michigan

Forms: Wire, bar, rod, sheet, strip, ribbonGeneral:

Nichrome V is one of the nickel-chromium alloys widely used for resistors and heater elements. The chemical composition given above is for Nichrome V in wire form. Strip form in general will have smaller percentages of manganese, silicon and iron.

Special Handling Techniques and Formability:

The annealed alloy is readily formed and bent at room temperature. Grids, anodes and supports can be stamped out of this material. Parts made

*Reg. T. M. Driver Harris Co.

**Reg. T. M. W. B. Driver Co.

***Reg. T. M. Hoskins Manufacturing Co.

of Nichrome V may be bright annealed in dry hydrogen with a dew-point of -50°C or lower. Stress relief takes place in about three hours at $600 - 700^{\circ}\text{C}$; cooling rate is not critical. Nichrome V like other nickel alloys, is sensitive to sulfurous atmospheres and to lead and phosphorous. Machineability is roughly 30% based on B-1112 steel - somewhat like Kovar in the ease with which it may be formed by turning, drilling or tapping. Design considerations must allow for the relative volatility of chromium in using Nichrome V at temperatures of 1000°C or higher.

Joining:

Spot-welding is the preferred method of joining Nichrome V to itself or to other materials such as nickel, tungsten or molybdenum, but typical brazing techniques with copper or silver-brazing alloys may also be used. (Oxide film should be removed in an acid etch prior to welding or brazing). Brazing may be accomplished in dry hydrogen or vacuum.

Allotropic Changes:

There is no change in crystal form with heating or cooling. Grain growth is not usually significant.

Ease of Outgassing:

Nichrome V must be handled cautiously when being outgassed to avoid evaporation and oxidation. The preferred method is a preliminary firing in dry hydrogen at about 1000°C for five to ten minutes followed by flashing at dull red heat (approximately 800°C) for an additional five to ten minutes during the exhaust processing. Heating to 1000°C in vacuum will cause noticeable evaporation since the vapor pressure at this temperature is approximately 1×10^{-6} mm Hg.

NICHROME V

Applications:

Nichrome V is useful for anodes, grids, grid supports, leads and other structures, especially those which may be formed by stamping or bending as opposed to machining.

Oxidation:

The mixture of nickel and chromium oxides which forms on Nichrome surfaces when heated in air serves to protect the base metal from further attack. This oxide layer is similar to that which forms on austenitic types of stainless steel. For maximum oxidation resistance, use a material low in carbon. For example, the useful life of 80 - 20 nickel-chromium alloy at 1100°C is reduced about one-half by the presence of .3% carbon. Manganese is also detrimental in this respect whereas silicon and aluminum improve oxidation resistance.

NICHROME V

Table 14
NICHROME V DATA

		<u>Ref.</u>
Density	8.41 g/cc	40
Melting Temperature	1400°C	40
Annealing Temperature	870 - 1040°C	37
Tensile Strength	99,000 Psi	7
Modulus of Elasticity	31×10^6 Psi	37
Yield Strength	53,000 Psi	7
Maximum Elongation	35%	7
Thermal Conductivity	.038 cal/cm/°C/sec	7
Specific Heat	.104 cal/g/°C	40
Linear Thermal Expansion	17.1×10^{-6} in/in/°C, 10° - 1000°C	40
Electrical Resistivity	108×10^{-6} ohm-cm at 20°C	40
Temp. Coefficient of Resistivity	$1.1 \times 10^{-4}/°C$	40
Temp. for 10^{-5} mm Vapor Pressure	1070°C	62, p. 29

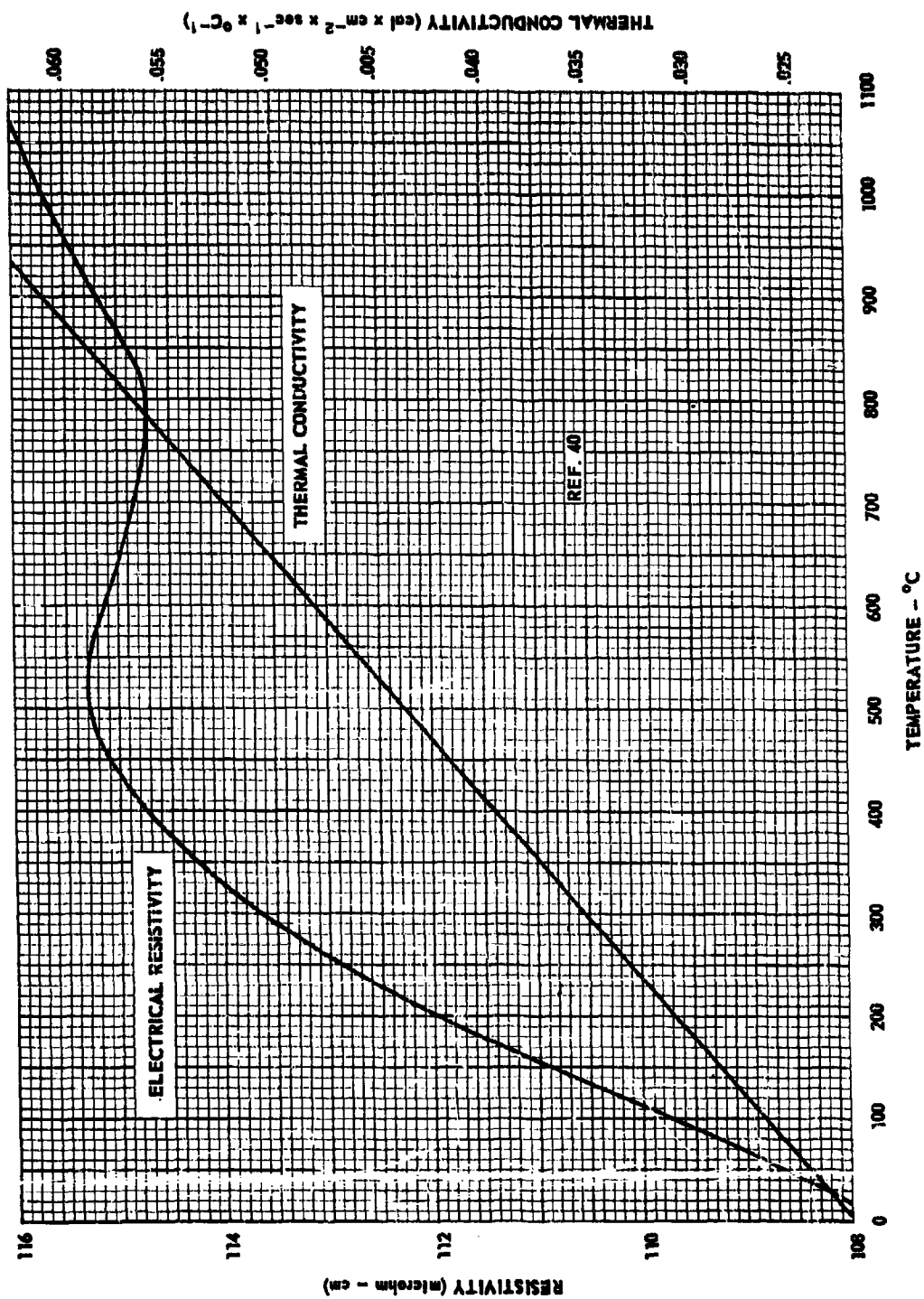


Fig. 52 — Thermal Conductivity and Electrical Resistivity of
80-20 Nickel-Chromium Alloy

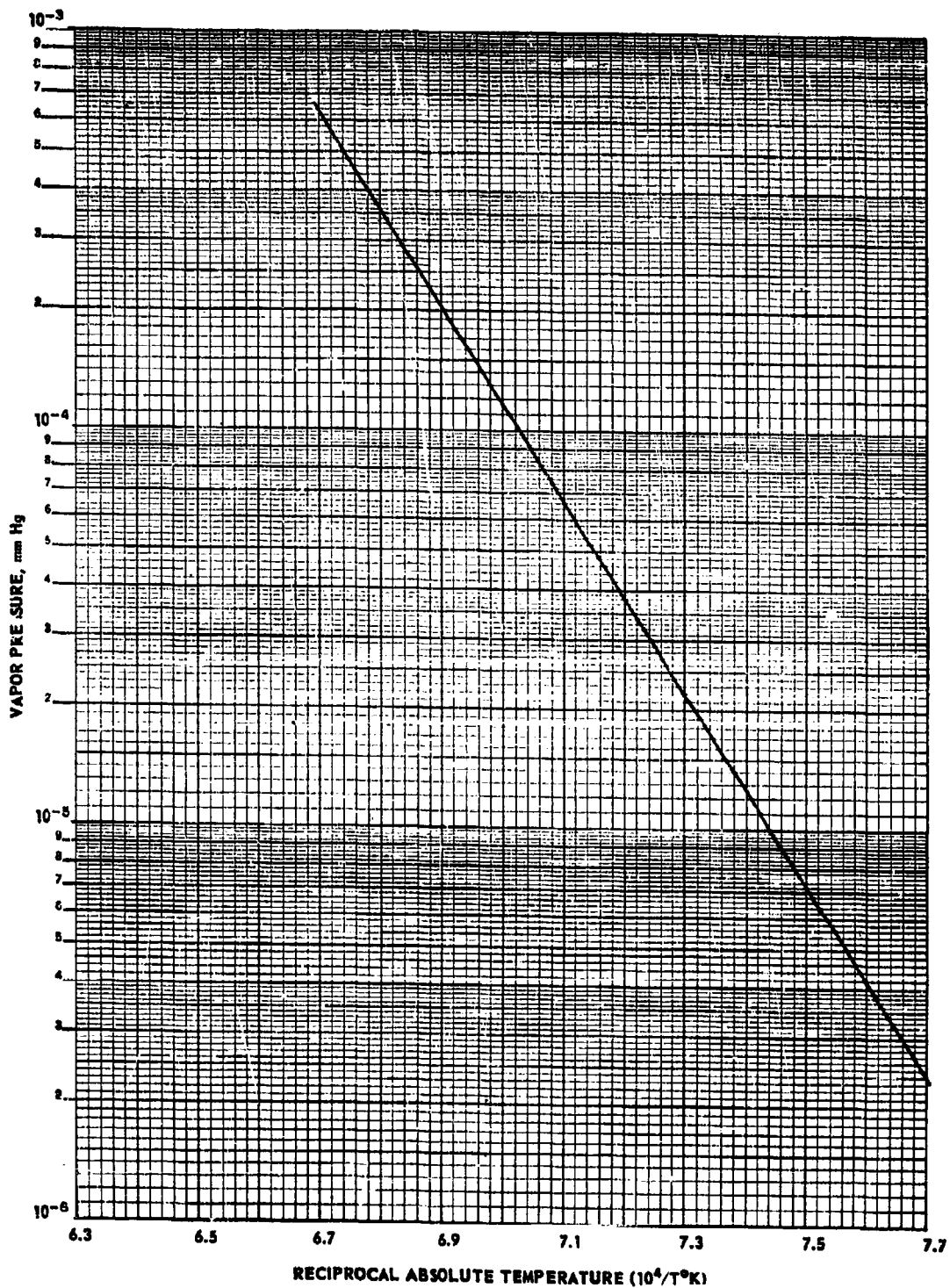


Fig. 53 — Vapor Pressure of 80-20 Nickel-Chromium Alloy

Material: NickelChemical Composition* for electronic grade "A" nickel (limiting values) %:

Nickel + Cobalt	- 99.00 Minimum	Silicon	- .15 Maximum
Manganese	- .35 Maximum	Iron	- .20 Maximum
Titanium	- .01 to .05	Magnesium	- .01 to .08
Copper	- .15 Maximum	Sulfur	- .008 Maximum
Carbon	- .15 Maximum		

Trade Designations: Electronic grade "A" nickel

Selected grade "A" nickel

High-purity nickel

Suppliers: Driver-Harris Co., 201 Middlesex St., Harrison, N.J.

The International Nickel Co., 67 Wall St., New York 5, N.Y.

Superior Tube Co., Box 191, Norristown, Penna.

Wilbur B. Driver Co., 1875 McCarter Highway, Newark 4, N.J.

Forms Available: Rod, bar, strip, wire, tube, powder, sheet, screen.General:

This report is concerned primarily with high-purity alloys containing more than 99% nickel plus cobalt, however, some descriptions are included of other compositions which are generally useful to the design engineer. More detailed information for these alloys can be found in the references.

The following quote from Ref. 12 illustrates the general properties and uses of nickel:

Ref. 12, p. 4

"A" nickel (electronic grade) is a selected grade of commercial purity wrought nickel produced by melting and deoxidizing electrolytic nickel. It is easily drawn and can be worked, welded and brazed (Ag or Cu) readily. Its resistance to corrosion is of a high order. Oxidation at high temperatures is low and any oxide scale formed is tightly adherent. Sufficient strength is retained at normal bombarding temperatures to prevent deformation during outgassing. Its modulus of elasticity and damping factor are high, minimizing vibrational and microphonic effects. The electrical resistivity is moderate, about 57 ohms per circular mil ft., at 32°F. (9.5 microhms/cm³ at 0°C), with a temperature coefficient of $4.1 - 5.1 \times 10^{-3}/^{\circ}\text{C}$. It is easily spot welded and heated by induction. The electrical conductivity at moderate temperatures is high enough to render it suitable as a current carrying lead. The high magnetostriction coefficient of nickel makes it useful in devices employing this principle. Nickel is magnetic at room temperature and becomes nonmagnetic near 360°C

The metallic elements listed in the chemical composition section have rather minor effects on the physical characteristics. Sulfur, however, is detrimental. In amounts over about .005% it may form NiS or Ni-NiS eutectic between grains, leading to embrittlement. If free carbon is present, some reduction in malleability can be expected. Phosphorus and lead must also be avoided.

Special Handling Techniques and Formability:

The general ease of working (machining, welding, brazing, flow properties) along with good strength at elevated temperature make nickel attractive for many tube structures. The magnetic effects may be either

minimized or enhanced by alloying with iron or other metals. In machining properties nickel is similar to AISI 1010 steel. Tools and work should be well supported to prevent chatter and backlash.

Nickel may be worked either hot or cold - there is no hot-shortness range as encountered with iron. Oxides may be removed by cleaning and pickling.

Allotropic Changes and Crystal Growth:

Pure nickel does not change its crystal structure on heating. Crystal growth begins at about 600°C but it is annealed at about 850 - 1050°C for five to ten minutes. Stress-relieved parts may be made by heating to 540 - 600°C for 3 hours.

Ease of Outgassing:

Nickel outgasses readily in vacuum at about 850°C in one hour after hydrogen firing at 950 - 1050°C for ten to fifteen minutes. Wires or thin plates will, of course, outgas more readily than heavier pieces. The firing and outgassing schedules lead to very soft annealed metal.

Joining Methods:

Nickel is readily welded, brazed or soldered to itself or other materials. Welding and brazing are best done in hydrogen or vacuum unless the part can be pickled before assembly. Brazing alloys containing phosphorus should not be used.

Sulfurous gases, or alternate oxidation - reduction cycling should be avoided. Mechanical fastening methods may also be used; the ease of machining and great malleability of nickel simplify assembly procedures.

Typical Applications:

Electroplating with nickel is popular for improving appearance, for corrosion resistance, or for the build-up of undersized parts. Nickel plating is also used as a well-adherent, compatible sub-coating when plating other metals such as copper or chromium. Other coating methods are also used, such as metal-spraying, vapor deposition from gaseous nickel-carbonyl, or vacuum evaporation. Powdered nickel is readily available for sintering with itself or other metals. Some uses of nickel in electron tubes are:

Cathodes	Getter tabs
Support wire and rods	Anodes
Grid side rods	Cathode shields
Base pins	

NICKEL ALLOYS FOR ELECTRONIC USES

"202" NickelComposition (%):

Nickel (+ Cobalt)	- 94.0 Minimum	Magnesium	- .01 - .10
Copper	- .20 Maximum	Titanium	- .02 Maximum
Iron	- .20 Maximum	Silicon	- .02 - .06
Manganese	- .20 Maximum	Sulfur	- .008 Maximum
Carbon	- .10 Maximum	Tungsten	- 3.50 - 4.50

General Characteristics:

This 4% tungsten, active cathode nickel alloy, is designed for increased strength and rigidity at elevated temperatures. In addition to these characteristics the tungsten addition imparts improved life, re-

liability and performance under fluctuating temperatures, as well as resistance to shock loading and high rated heater voltages.

Typical Uses:

Cathode Base Metal (seamless, welded and drawn, lockseam and discs)

Availability: Strip and ribbon, cold rolled
Tubing-seamless, welded and drawn

"220" Nickel*

Nickel (+ Cobalt)	- 99.00 minimum	Magnesium	- .01 - .08
Copper	- .10 Maximum	Titanium	- .01 - .05
Iron	- .10 Maximum	Silicon	- .01 - .05
Manganese	- .20 Maximum	Sulfur	- .008 Maximum
Carbon	- .08 Maximum		

General Characteristics:

"220" nickel is used as a cathode base metal where fairly easy activation is required, but without the liberation of excessive amounts of free barium. This falls in the A.S.T.M. classification as Active Cathode Type material. As in all grades produced especially for use in cathodes, the copper, iron and manganese contents are closely controlled and are held at low levels. Magnesium is controlled to .08% maximum as sublimation of this element is sometimes objectionable.

Typical Uses:

Cathode base metal (disc, lockseam, seamless and lapseam)

Availability: Tubing, seamless, cold drawn
Tubing, welded, cold drawn
Strip and ribbon, cold rolled

*Ref. 12

NICKEL

"225" Nickel*

Nickel (+ Cobalt)	- 99.00 Minimum	Magnesium	- .01 - .08
Copper	- .10 Maximum	Titanium	- .005 Maximum
Iron	- .10 Maximum	Silicon	- .15 - .25
Manganese	- .20 Maximum	Sulfur	- .008 Maximum
Carbon	- .08 Maximum		

General Characteristics:

"225" nickel exhibits a higher activity than "220" nickel which has a silicon content of 0.01 - 0.05%. It is used for oxide coated cathodes where activation under adverse conditions is essential. The high reducing agent content probably tends to liberate appreciable barium. This characteristic should be borne in mind in considering this material, as it is sometimes a limitation. It is produced as seamless, welded and drawn, lockseam or lapseam tubing for use as indirectly heated oxide-coated cathodes in electronic devices.

Typical Uses:

Cathode base metal (seamless, lockseam, lapseam and disc)

Availability:

Tubing, seamless, cold drawn
Tubing, welded, cold drawn
Strip and ribbon, cold rolled

*Ref. 12

NICKEL

"330" Nickel*

Nickel (+ Cobalt)	- 99.00 Minimum	Magnesium	- .01 - .10
Copper	- .10 Maximum	Titanium	- .005 Maximum
Iron	- .10 Maximum	Silicon	- .10 Maximum
Manganese	- .30 Maximum	Sulfur	- .008 Maximum
		Carbon	- .10 Maximum

General Characteristics:

"330" nickel was designed primarily for the electronic industry for plates (anodes) in vacuum tubes. It is also used for oxide coated and cold cathode applications and for other structural parts of tubes.

Typical Uses: Plates (anodes)

Structural parts

Cathode base metal (welded, drawn, lockseam, lapsed and
disc)

Magnetostrictive devices

Availability: Strip and ribbon, cold rolled

"Duranickel"*

Nickel (+ Cobalt)	- 93.00 Minimum	Silicon	- 1.00 Maximum
Copper	- .25 Maximum	Aluminum	- 4.00 - 4.75
Iron	- .60 Maximum	Sulfur	- .01 Maximum
Manganese	- .50 Maximum	Titanium	- .25 - 1.0
Carbon	- .30 Maximum		

*Ref. 12

General Characteristics:

"Duranickel" is an age-hardenable wrought nickel-aluminum alloy with mechanical properties between "K" Monel and Inconel "X". The properties of the alloy in the soft condition may be increased by cold work, and this may be supplemented by the aging treatment. Its selection over the softer nickels is usually based on mechanical considerations rather than other physical characteristics. In the annealed and aged condition it exhibits low relaxation and thus is useful for spring parts subjected to relatively high stress up to 350°C, for prolonged times, and may be employed up to 400°C at low stress and short time at temperature. The alloy is slightly magnetic at room temperature in the soft condition and magnetic after age-hardening. It has corrosion resistance comparable with "A" nickel. For best surface condition, aging in dry hydrogen is recommended, but even in this gas a thin tenacious aluminum oxide film is formed which must be removed prior to welding or soldering. Its electrical resistivity is about 45 microhms/cm³ at 20°C.

Typical Uses: Clips, diaphragms, springs.

Availability: Mill forms including: Strip and ribbon, cold rolled

Wire, cold drawn

Rods and bars, cold drawn or hot rolled

"Low Carbon Nickel"*

Nickel (+ Cobalt)	- 99.00 Minimum	Carbon	- .02 Maximum
Copper	- .25 Maximum	Silicon	- .35 Maximum
Iron	- .40 Maximum	Sulfur	- .01 Maximum
Manganese	- .35 Maximum		

*Ref. 12

NICKEL

General Characteristics:

This alloy has a maximum carbon content of 0.02%, which results in a material that is soft, ductile, and more suitable for spinning and cold coining operations due to its low base hardness and low rate of work hardening.

It is not generally recommended for deep drawing applications, commercial "A" nickel being preferred. Low carbon nickel is preferred for long time service in applications under stress at temperatures in the 375 to 650°C range.

Typical Uses: Getter tabs, heating element sheathing, spun anodes, special purpose electron tubes, structural components.

Availability: Mill forms including: Rod and bar, hot rolled or cold drawn
Strip, cold rolled
Sheet, cold rolled
Wire, cold drawn
Tubing, seamless
Tubing, welded
Plate

Note: The description of the nickel alloys given above were taken from "Inco Nickel Alloys for Electronic Uses" with the permission of the International Nickel Company.

NICKEL

Table 15
NICKEL DATA

		<u>Ref.</u>
Density	8.89 gm/cc	2, p. 10-5
Lattice Type	Face-centered cubic	13
Melting Point	1440 \pm 5°C	13
Modulus of Elasticity	30 x 10 ⁶ psi	13
Thermal Conductivity	.145 cal/cm/sec/°C (0 - 100°C)	13
Specific Heat	.105 cal/g/°C	13
Total Emissivity	25°C - 0.045 1000°C - 0.19 100°C - 0.06 500°C - 0.096	13 13 14 14
Curie Point	360°C	13
Magnetic Permeability	μ max. = 1000 gauss, H = 20 oersteds	13
Work Function	4.61 eV	50
Richardson Constant 'A'	30	50
Coefficient Linear Thermal Expansion	16.3 x 10 ⁻⁶ in/in/°C, (25 - 900°C)	13
Temp. for 10 ⁻⁵ mm Vapor Pressure	1130°C	81
Tensile Strength	41,000 psi	7
Yield Strength	8,000 psi	7
Maximum Elongation	28%	7
Electrical Resistivity	6.84 x 10 ⁻⁶ ohm-cm	7
Temp. Coefficient of Resistivity	68 x 10 ⁻⁴ /°C	7

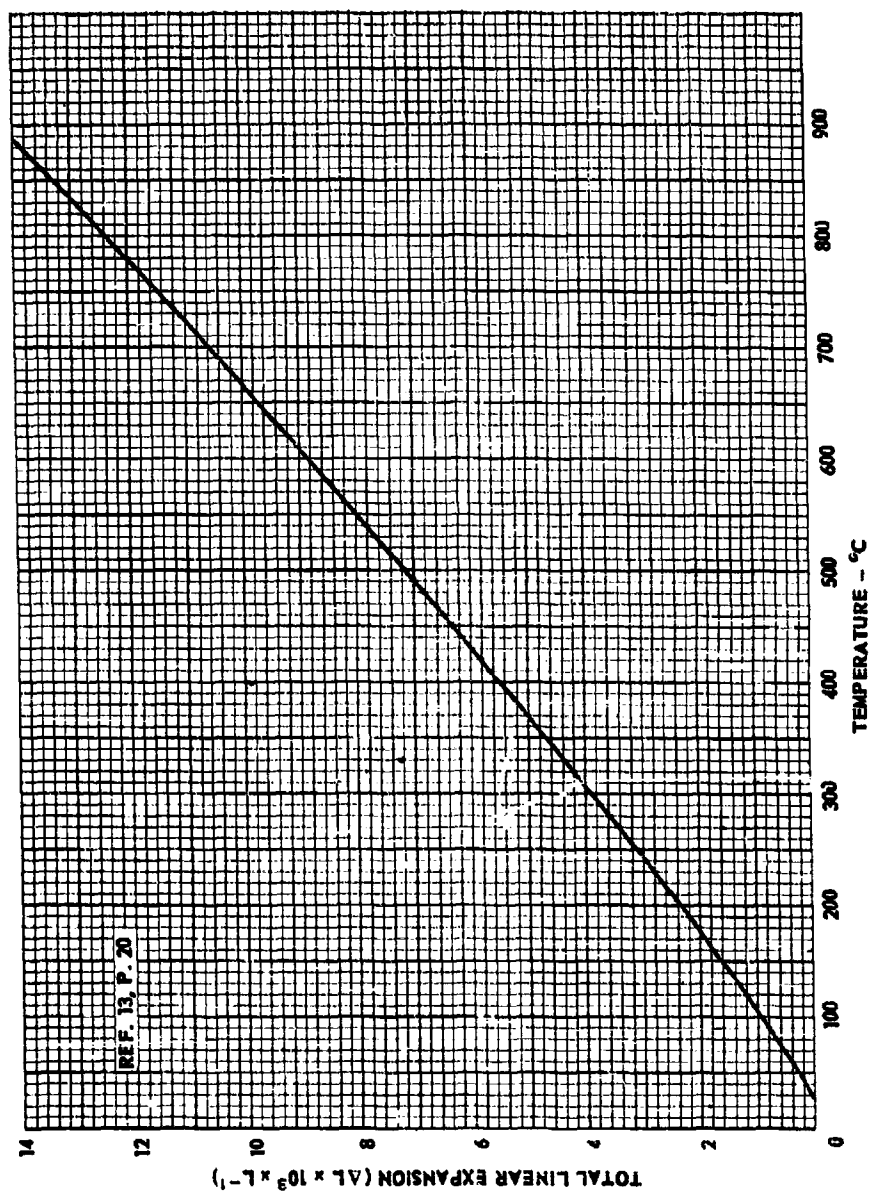


Fig. 54 — Linear Thermal Expansion of Nickel

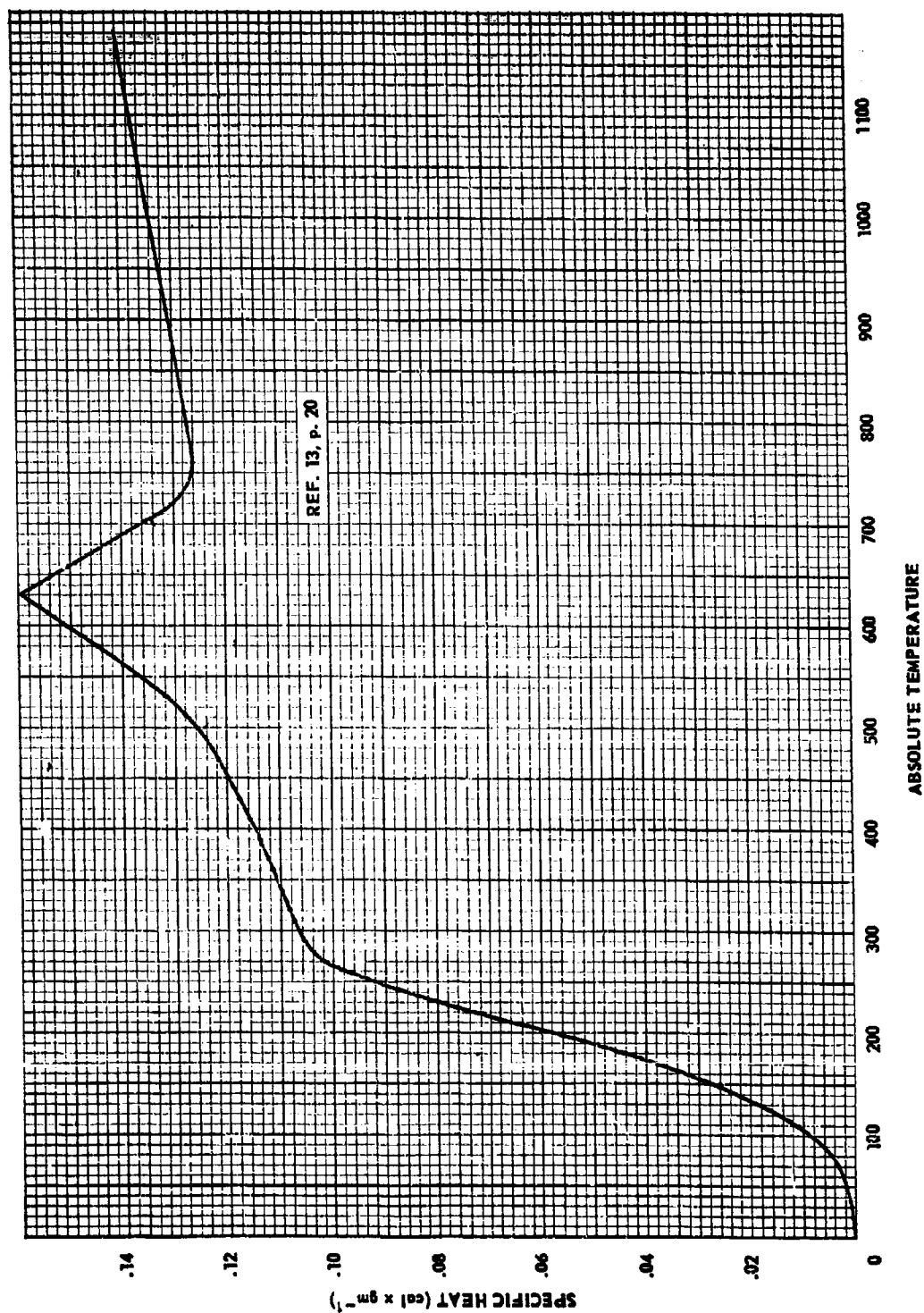


Fig. 55 — Specific Heat of Nickel

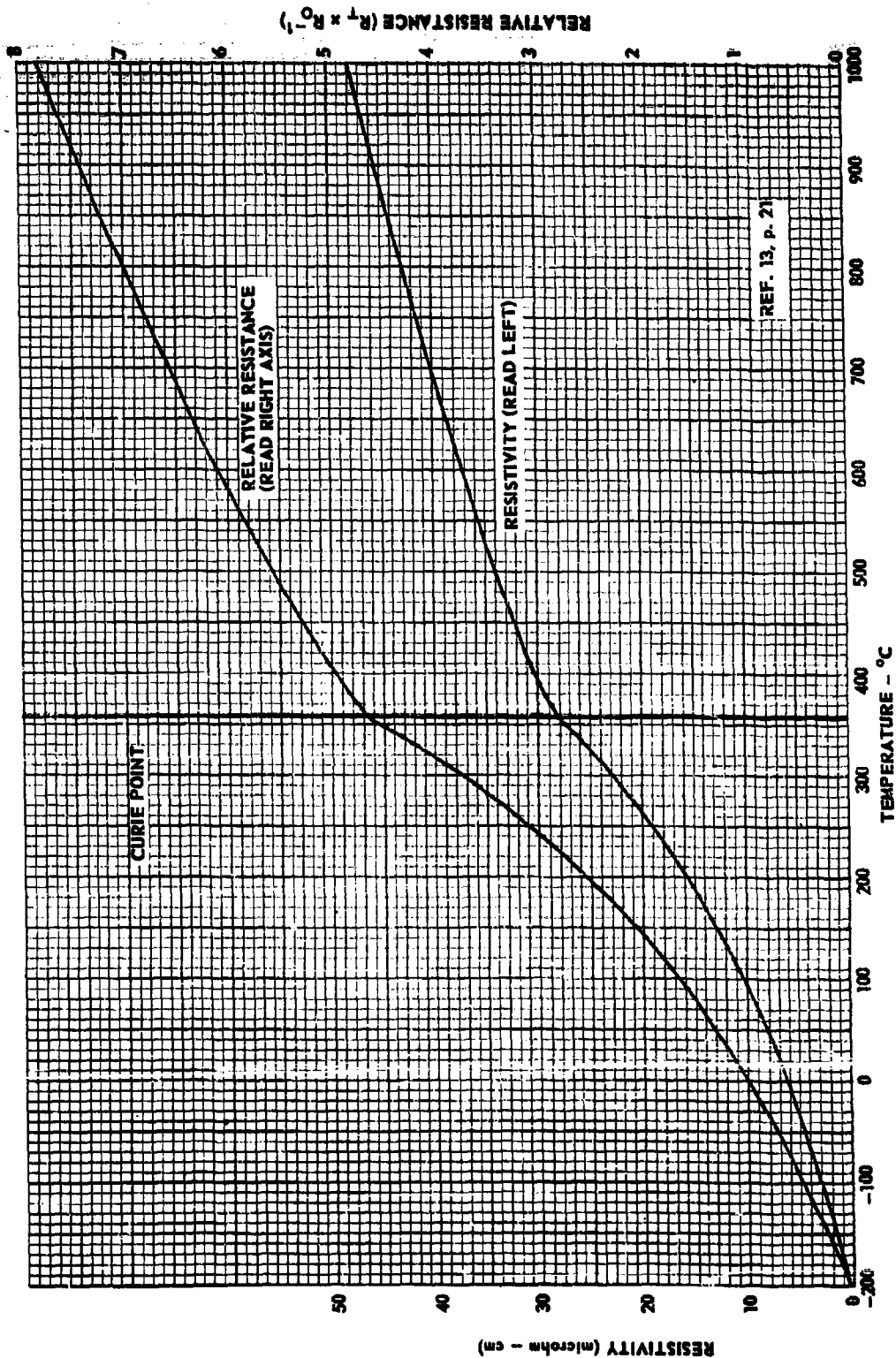


Fig. 56 — Electrical Resistivity of Nickel

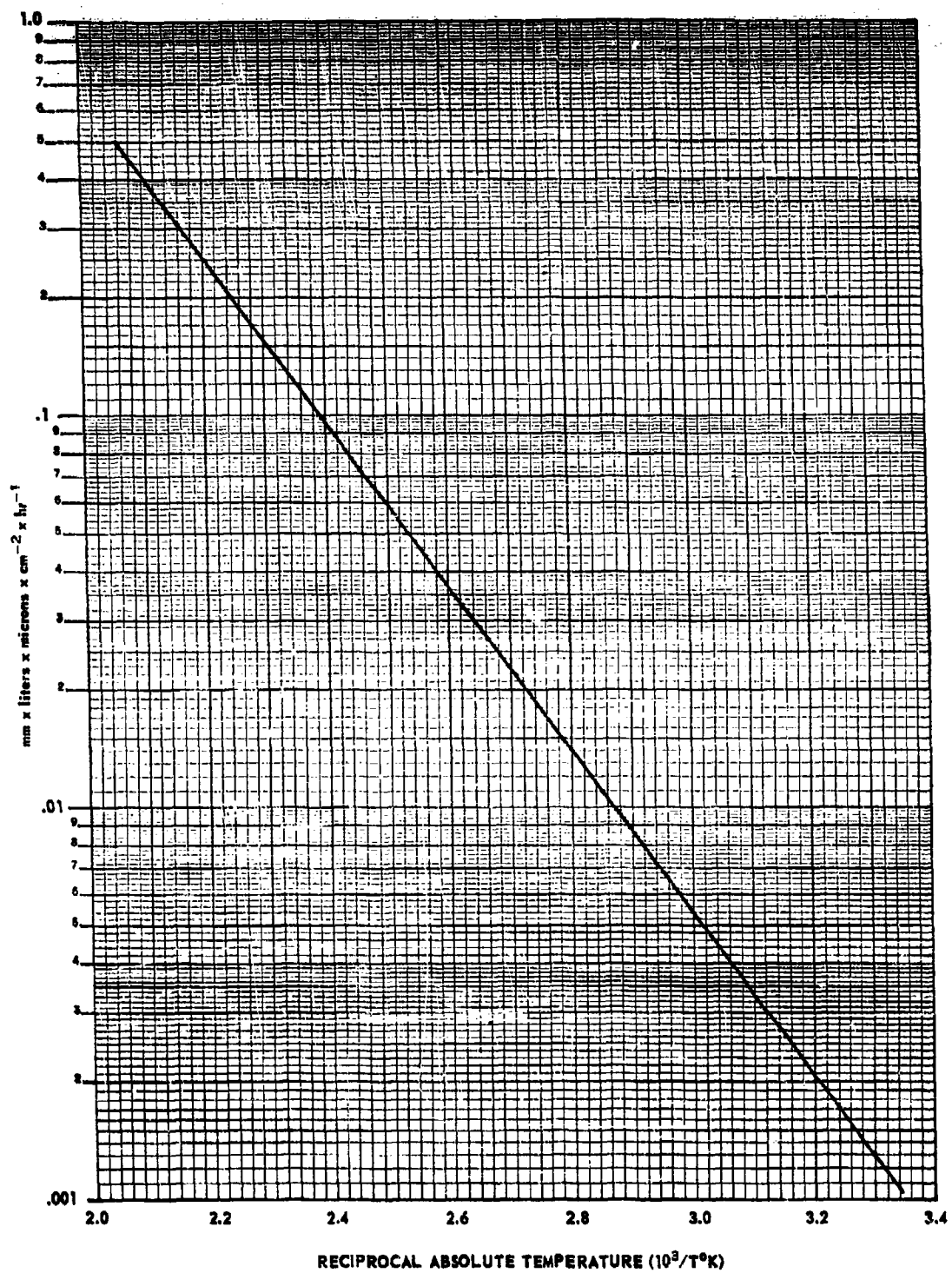


Fig. 57 — Hydrogen Permeation Through Nickel

PLATINUM

Material: Platinum

Chemical Composition: 99.9% Min. Pt.

Trade Designation: Platinum

Suppliers: Baker & Co., 113 Astor St., Newark 2, N.J.

Bram Metallurgical-Chemical Co., 820 65th Ave., Philadelphia, Pa.

J. Bishop & Co., Malvern, Pa.

Handy & Harman, 82 Fulton St., New York 38, N.Y.

Sigmund Cohen Mfg. Co., 121 South Columbus Ave., Mt. Vernon, N.Y.

Wester Gold & Platinum Co., 525 Harbor Blvd., Belmont, Calif.

Forms Available: Powder, wire, foil, sheet, brazing preforms, special shapes

General:

Because of its high cost the use of platinum is most often limited to plating or cladding on one of the base metals, or brazing alloys. One of the principal reasons for its use is the suppression of primary or secondary electron emission from grids, anodes and supporting structures. Since platinum has relatively low vapor pressure, grids and anodes coated with it may be operated at reasonably high temperatures (to 1000°C) without fear of excessive evaporation.

Special Handling Techniques and Formability:

In electroplating, the usual technique of copper flashing followed by nickel plating and then depositing the precious metal on the surface of the nickel, is sometimes inadequate. If temperatures of operation will rise above 600° or 700°C, it is recommended that molybdenum or tungsten be

employed as the base metal and plated directly with platinum. No inter-diffusion will occur with these metals at these temperatures. A thin carbon coating applied to a base metal surface will also prevent platinum diffusion.

Special Handling Techniques and Formability:

Cladding is sometimes recommended because of the additional platinum thickness which may be obtained. Tungsten can be successfully clad with platinum and is available commercially.

In the preparation of plating baths and cleaning solutions sulfur must be excluded or removed. Very small traces of sulfur will lead to rapid failure of cathodes.

Joining:

Platinum may be spot-welded or it may be brazed using standard copper or silver brazing alloys. Mechanical fastening is also recommended.

Allotropic Changes:

There are no allotropic changes on heating or cooling. The face-centered cubic structure is retained from room temperature up to the melting point.

Ease of Outgassing:

Since platinum is quite inert, reaction with gases is not much of a problem. The metal may be outgassed readily at 1000°C in vacuum and for most applications a simple bakeout at $400 - 450^{\circ}\text{C}$ is adequate.

Applications:

Platinum surfaces are recommended for use in tubes with thoriated tungsten emitters; evaporated thorium (like barium on gold) will diffuse beneath the

PLATINUM

surface and have little effect on the work-function of the platinum.

Brazing alloys using platinum as an essential constituent are frequently used in microwave tubes. In general, these alloys combine ready availability, good wetting and flow characteristics, low vapor pressure, excellent resistance to oxidation and reasonably good strength at elevated temperatures. Intergranular attack of nickel alloys, such as kovar and stainless steel, is not a problem. Platinum may be used alone as a brazing material or it may be alloyed with copper, palladium or gold in either binary or ternary compositions. Some of these compositions wet tungsten and molybdenum and other high temperature metals such as Inconel and may be used for brazing these materials. Platinum and its alloys are frequently used in step brazing.

An important use of platinum and its alloys is in the production of thermo-couples for use up to about 1500°C . The well-known Pt/Pt-10Rh couple has been used for many years as a standard temperature measuring device. Platinum wire is also used for resistance thermometers.

Besides its use inside the tube envelope, platinum is sometimes found in exterior resistive components and on surfaces which must remain free of oxides or other corrosion products.

Platinum filaments are also used in Pirani gauges.

PLATINUM

Table 16
PLATINUM DATA

		<u>Ref.</u>
Density	21.5 g/cc	82
Lattice Type	Face-centered cubic	82
Melting Temperature	1774°C	82
Annealing Temperature	800° - 1200°C	82
Tensile Strength	18,000 Psi	82
Yield Strength	3,500 Psi	82
Modulus of Elasticity	21 x 10 ⁶ Psi	82
Maximum Elongation	40%	82
Thermal Conductivity	.17 cal/cm/sec/°C	82
Specific Heat	.032 cal/g/°C	82
Linear Thermal Expansion	10.2 x 10 ⁻⁶ in/in/°C (0 - 1000°C)	82
Electrical Resistivity	9.81 x 10 ⁻⁶ ohm-cm	82
Temp. Coefficient of Resistivity	39.8 x 10 ⁻⁴ /°C	82
Curie Point	Nonmagnetic	
Electron Work Function	5.32 eV	50
Richardson Constant 'A'	32	50
Temp. for 10 ⁻⁵ mm Vapor Pressure	1602°C	81

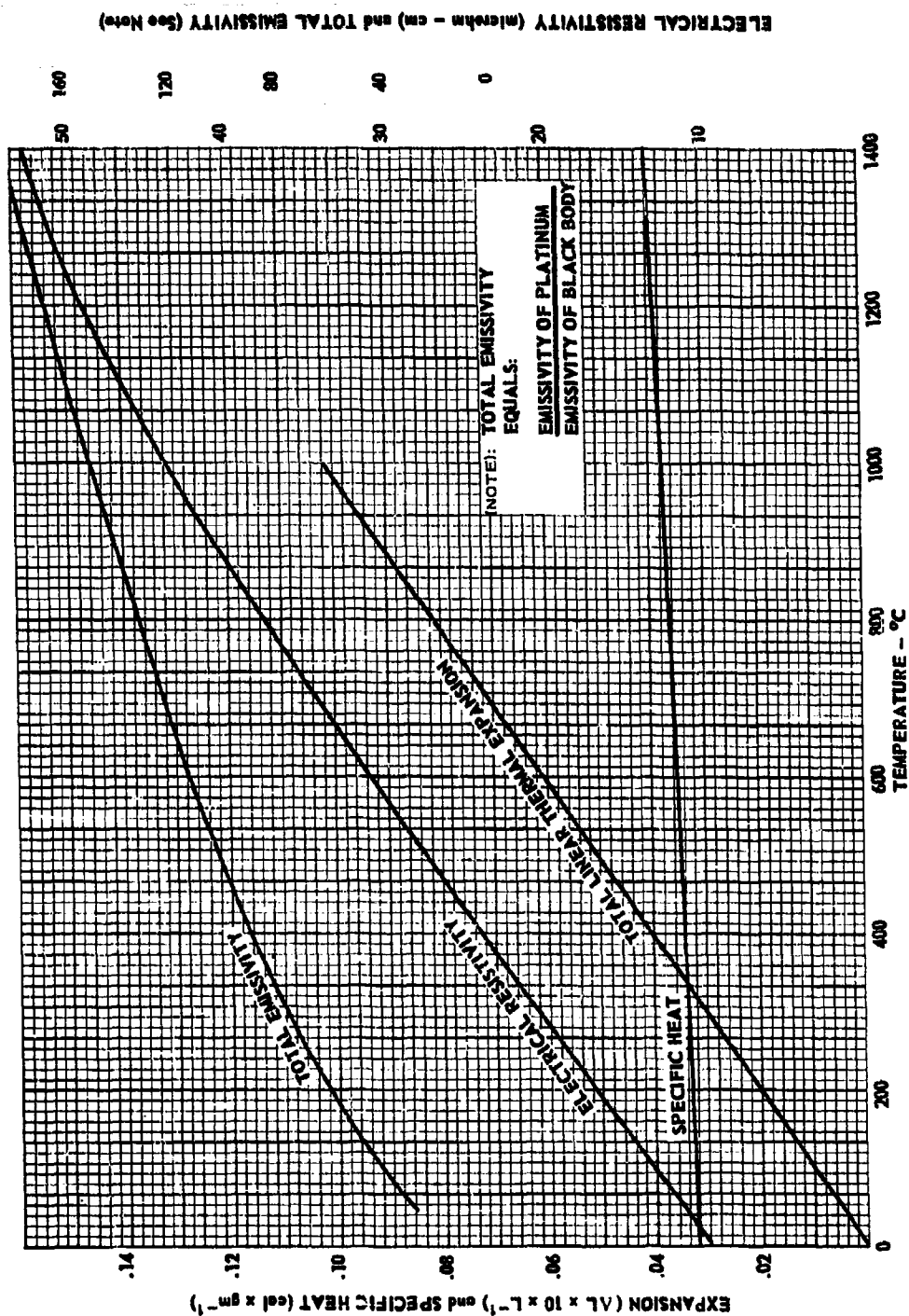


Fig. 58 - Thermal Emissivity, Electrical Resistivity, Specific Heat and Linear Thermal Expansion of Platinum

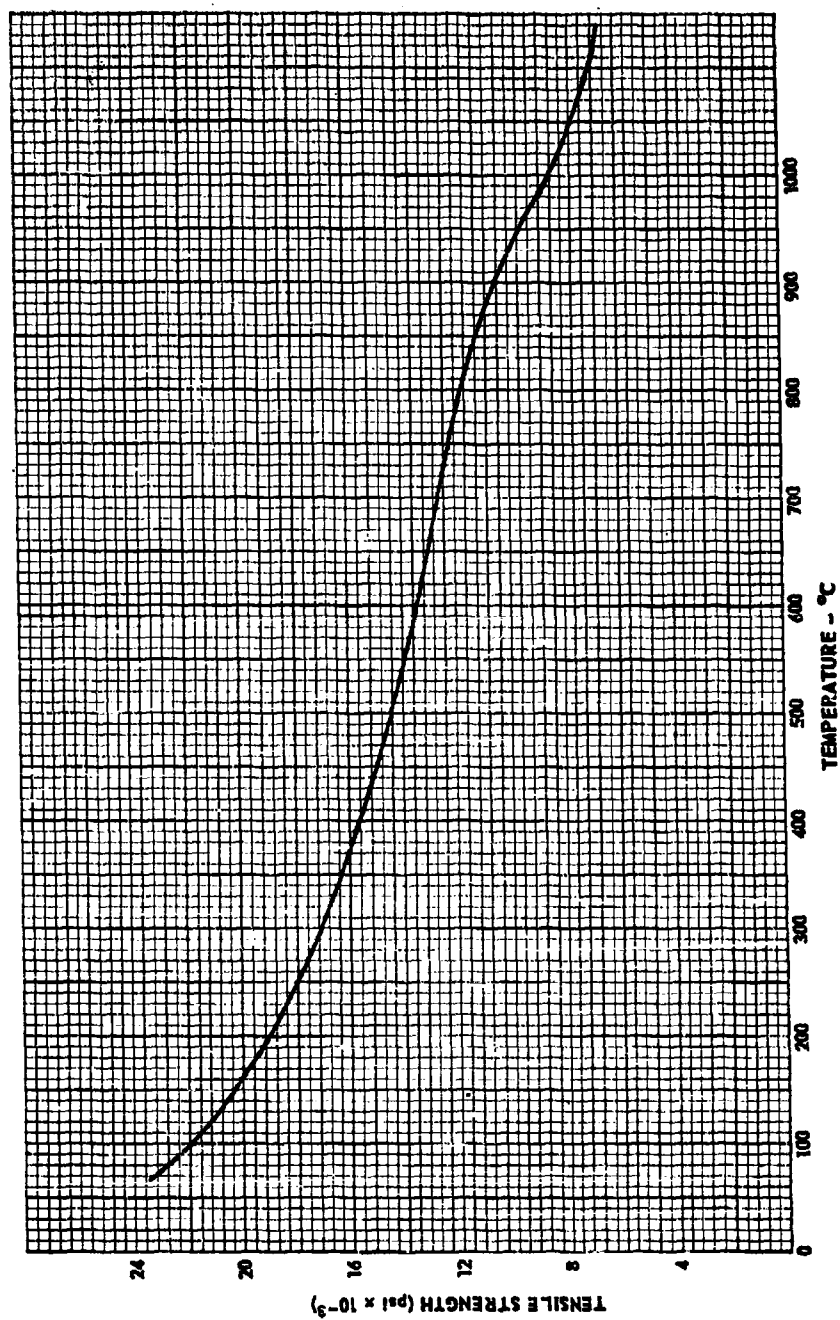


Fig. 59 — Tensile Strength of Platinum

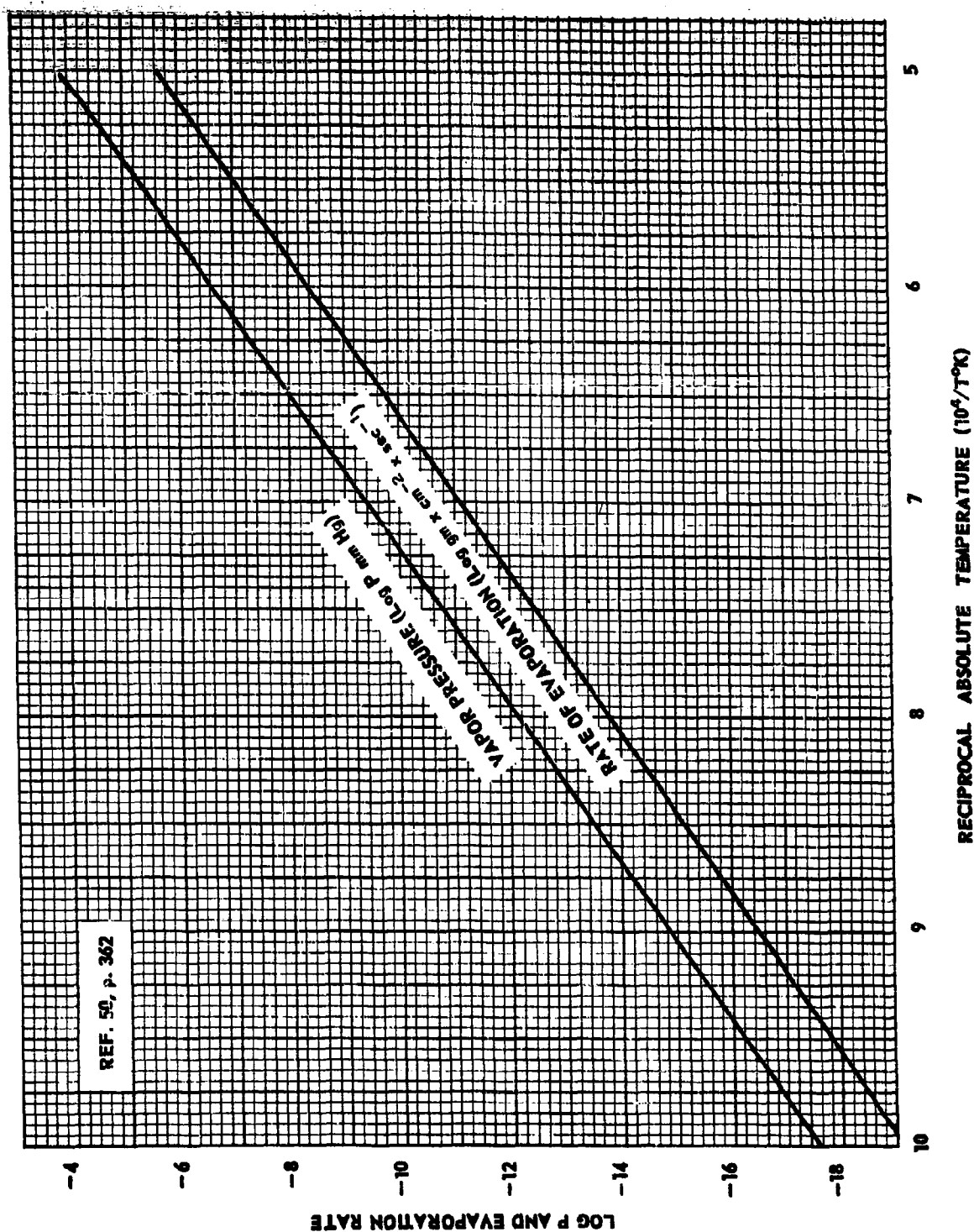


Fig. 60 -- Vapor Pressure and Evaporation Rate of Platinum

RHENIUM

Material: Rhenium

Chemical Composition: 99.8% Re Minimum

Trade Designation: Rhenium

Suppliers: University of Tennessee, Chemistry Dept., Knoxville, Tennessee
The Chase Brass & Copper Co., Torrington, Conn.

Forms Available: Powder, bar, strip, wire

General:

Rhenium is a member of group VIIA of the periodic table, falling between tungsten and osmium. It has a high melting point, low vapor pressure, and high strength at elevated temperatures. Because of the high cost (about the same as platinum) and the difficulty of working, rhenium is not expected to find much use except in those applications where its special properties are necessary.

The chemistry of rhenium has been thoroughly investigated during the past thirty years, but until the work done by C. T. Sims and his coworkers^{51,59} at Battelle Memorial Institute between 1952 and 1956, little was known about the metallurgical properties. These investigators prepared samples of purified rhenium and subjected it to various reduction methods in attempts to make wire, sheet and foil.

Rhenium may be used as one element in a high-temperature thermocouple in conjunction with platinum, tungsten, molybdenum or tantalum.

Thoriated rhenium is less effective than thoriated tungsten as an electron emitter. Rhenium makes a good contact material for resistive loads; the oxide is a fairly good conductor of electricity.

Special Handling Techniques and Formability:

Rhenium is produced in powder form and sintered in a hydrogen atmosphere or vacuum in a manner analogous to that used with tungsten. It may also be electroplated from an acid solution of potassium or ammonium perrhenate. The plating can be stabilized against corrosion by firing in hydrogen at about 1000°C .

Reduction of the massive material by swaging and rolling is impractical at high temperature; rhenium must be worked at or near room temperature. Machining is very difficult or impossible because of the rapid work hardening. Parts may be formed, however, by cold reduction to the sizes desired with intermediate anneals at 1700°C after each 10% to 40% reduction. Once the material has been obtained as wire or sheet, it may then be formed by cold-bending operations with reasonable success.

Joining:

Rhenium may be spot-welded or brazed to itself or to other metals. Mechanical fastening is not recommended.

Allotropic Changes:

There are no allotropic changes on heating or cooling. The hexagonal close-packed crystal structure is retained up to the melting point.

Ease of Outgassing:

Rhenium may be fired in hydrogen and outgassed to temperatures of 2000°C or more if this is necessary. It is not as reactive as tantalum

RHENIUM

and need not be protected from gas absorption while cooling.

Applications:

The availability of rhenium is so recent that there are no proven applications listed for it which would apply to microwave work. A number of experimental uses have been found which indicate that it may be useful in some areas. For example, it has shown much promise as a filament material and has been used in a field emission microscope, in vacuum gauges, and as a carrier for the evaporation of silver and nickel.

RHENIUM

Table 17
RHENIUM DATA

		<u>Ref.</u>
Density	20 g/cc	5
Lattice Type	Close-Packed Hexagonal	5
Melting Temperature	3170 \pm 50	5
Tensile Strength	164,000 Psi	51
Yield Strength (0.2% Offset)	46,000 Psi	51
Modulus of Elasticity	67.5 $\times 10^6$ Psi	
Thermal Conductivity	.17 cal/cm/sec/ $^{\circ}$ C	7
Specific Heat	.033 cal/g/ $^{\circ}$ C	5
Linear Thermal Expansion	6.8 $\times 10^{-6}$ in/in/ $^{\circ}$ C (20 - 1000 $^{\circ}$ C)	51, p. 57
Electrical Resistivity	21 $\times 10^{-6}$ ohm-cm	5
Temp. of Coefficient of Resistivity	31 $\times 10^{-4}$ / $^{\circ}$ C	5
Curie Point	Nonmagnetic	5
Electron Work Function	5.1 eV	50
Richardson Constant 'A'	200	50
Temp. for 10^{-5} mm Vapor Pressure	2377 $^{\circ}$ C	81

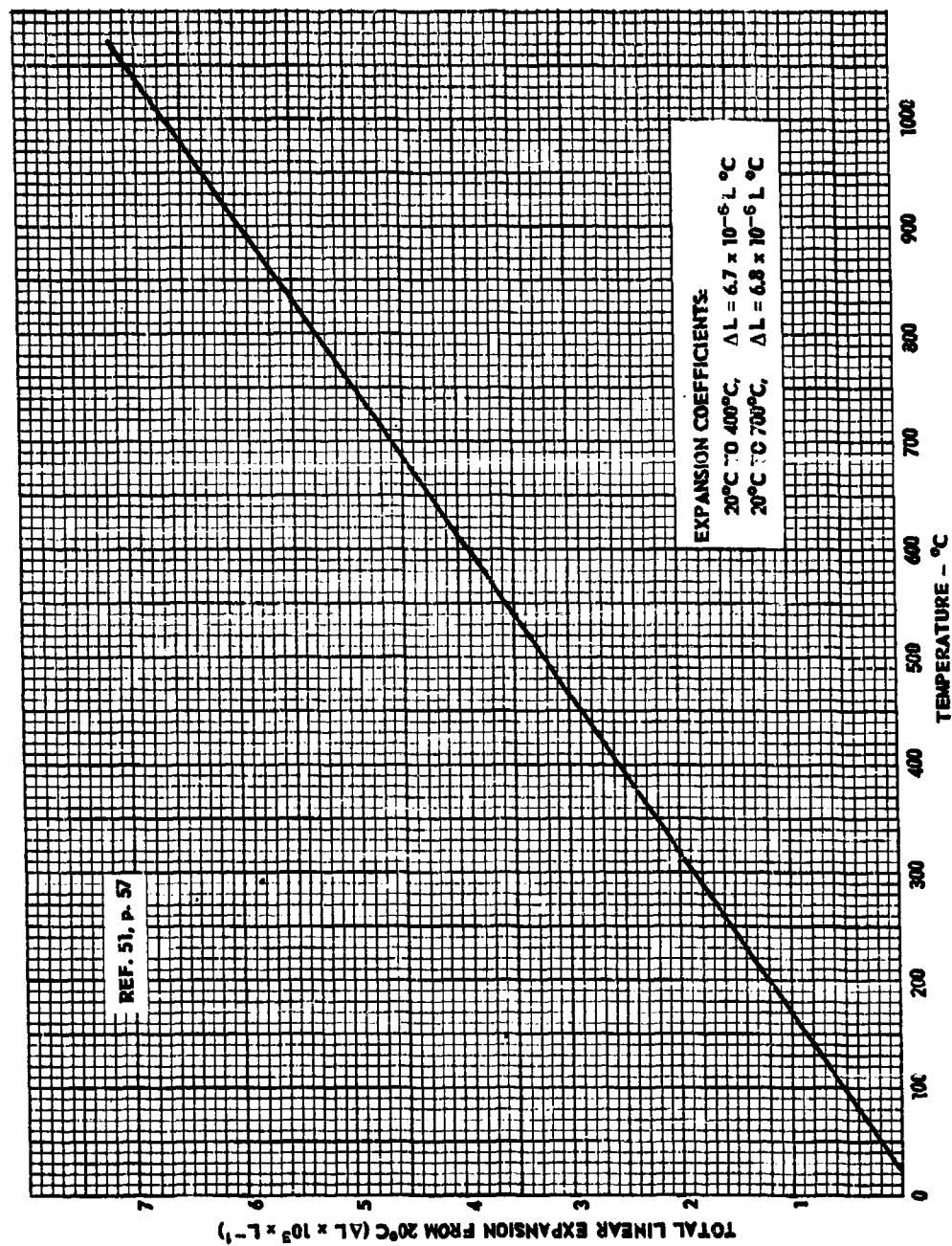


Fig. 61 -- Linear Thermal Expansion of Rhenium

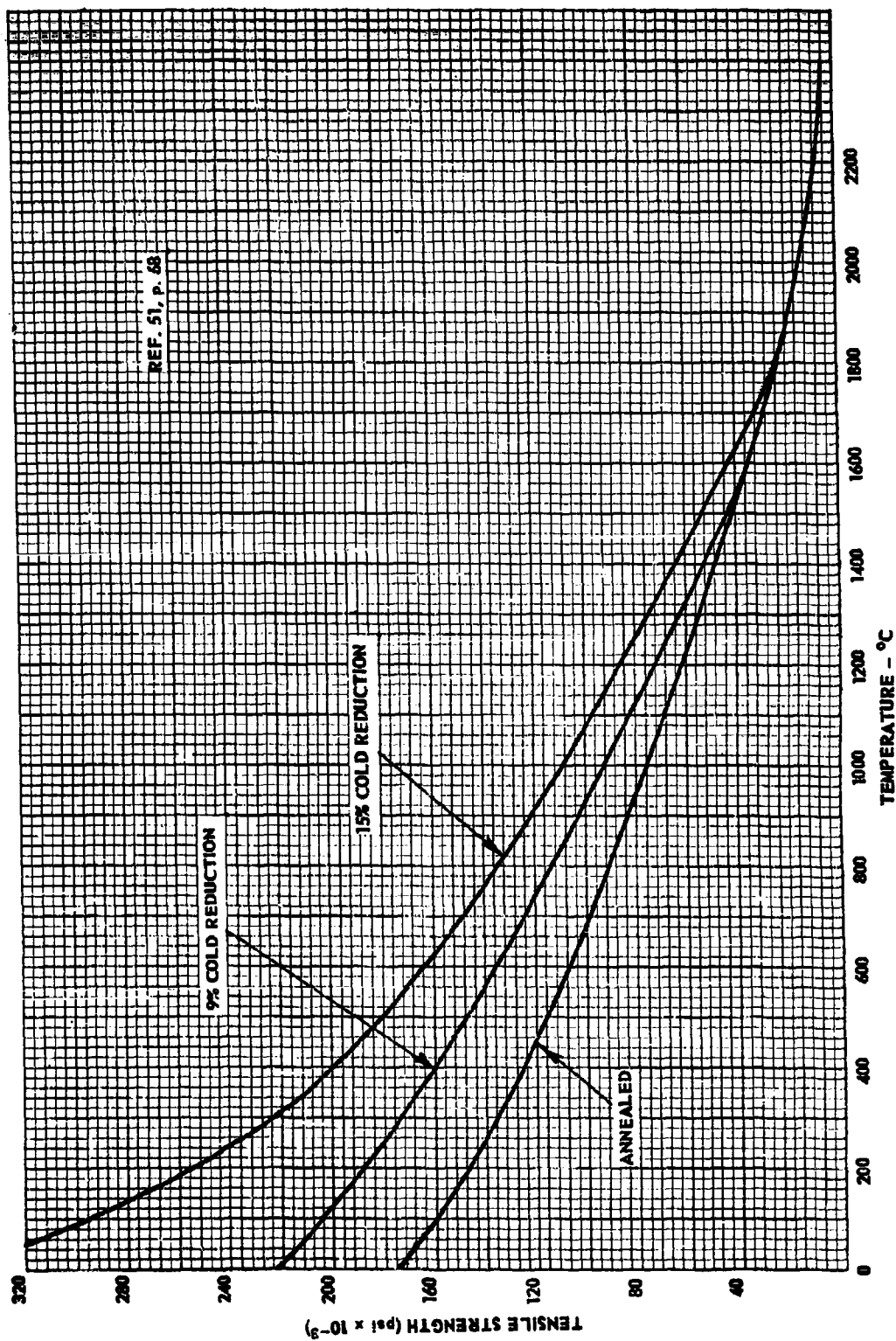


Fig. 62 — Tensile Strength of Rhenium

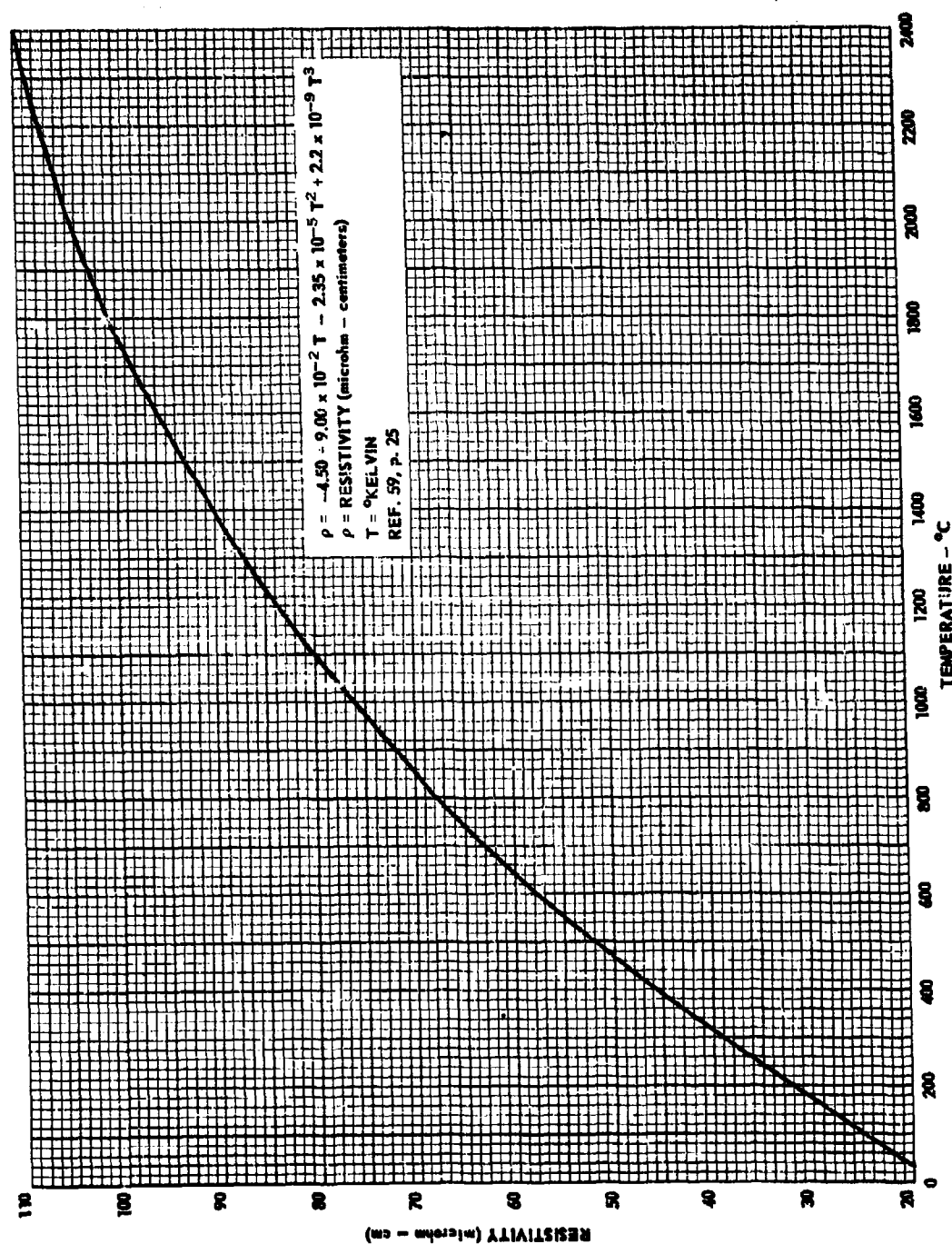


Fig. 63 — Electrical Resistivity of Rhenium

Material: Stainless Steel (Type 304)

Chemical Composition (%):*

Carbon	- .08 Maximum	Silicon	- 1.00 Maximum
Chromium	- 18.00 - 20.00	Iron	- Remainder
Manganese	- 2.00 Maximum		
Nickel	- 8.00 - 12.00		

Type 304L-Carbon - .03 Maximum, all others as shown above

Trade Designations: Low-carbon 18-8 stainless, AISI #304, AISI #304L

Suppliers: Allegheny-Ludlum Steel Corp., Pittsburgh 22, Pa.

Armco Steel Corp., Middletown, Ohio

Republic Steel, Cleveland 1, Ohio

Sharon Steel Corp., Sharon, Pa.

United States Steel, Pittsburgh 30, Pa.

Forms Available: Sheet, strip, rod, pipe, tube, powder, wire.

General:

Type 304 stainless is generally recommended for microwave tube work where a corrosion-resistant nonmagnetic alloy is required.

Following is a partial list of 300 series (nonmagnetic) steel alloys, with some brief comments on their composition and use:

<u>Type</u>	<u>Comment</u>
302	Most generally available - wide usage for architecture, trim, automobile, etc. up to 0.15% carbon.
303	Free-machining - contains sulfur - must not be used for tube parts inside the vacuum envelope.

<u>Type</u>	<u>Comment</u>
304	Lower carbon than 302; used for parts and jigs--0.08% maximum carbon.
304L	.03% maximum carbon - better than 304 for cyclic heating and cooling.
305	Low work-hardening, less subject to magnetic change during machining or cold-working. 0.12% maximum carbon.
308	Higher chromium and nickel than above--0.08 maximum carbon. Better than type 304 where carbide precipitation is a problem.
310	Also higher chromium and nickel, 0.25 carbon maximum. Lower thermal expansion than any of above--more adherent protective scale. Good for cyclic heating and cooling.
316	Molybdenum 2 - 3%, carbon .08% maximum. Resistant to chloride solutions.
317	Molybdenum 3 - 4% carbon .08% maximum. Better resistance than 316.
321	Titanium-stabilized against carbide precipitation. 0.08% carbon maximum.
347	Columbium-stabilized against carbide precipitation. 0.08% carbon maximum. Better corrosion resistance than 321.

The selection of the most suitable steel for a particular application may be quite involved and require extensive testing. The type which is chosen should offer a combination of availability, ease of machining and joining, moderate cost, and sufficient versatility for its various applications. Another factor of concern is the possibility of confusion which may arise when different grades of stainless are stocked together. For general use in the construction of microwave tubes, type 304 stainless offers a good

STAINLESS STEEL

balance of properties. It may be used inside the tube or externally; it also makes good brazing jigs for subassemblies and finished tubes. Jig parts should be oxidized in wet hydrogen at 1100°C for about 30 minutes to form an inert coating which is not readily wet by the common brazing alloys. Occasional reoxidation is necessary for those jigs which are used in dry hydrogen above 1100°C .

The austenitic steels generally cannot be precipitation hardened; cold-working is the only method available for hardening. There is some production of ferrite on cold working or machining and this must be considered if nonmagnetic material is required. Most applications in microwave tube construction call for the fully-annealed nonmagnetic material.

Special Handling Techniques and Formability

Type 304 stainless is readily deep-drawn, bent and forged. Forging should be done hot because of the hardening which occurs at room temperature. Recommended forging temperature is in the range between 1200°C to 925°C .

Machinability is about 50% of that of B1112 steel. Excessive roughing cuts should not be used because the surface becomes too hard for economical work. Best results are obtained by using positive rake single point tools at 400 - 500 sfpm with light feeds and depths of cut.

Exposure to sulfur in a reducing atmosphere may lead to embrittlement and early failure. Thin parts should not be heated in flames containing sulfurous gases.

STAINLESS STEEL

Allotropic Changes and Crystal Growth:

The austenitic structure (face-centered cubic) is retained throughout the working range with 304 alloy. Some reversion to ferrite (body-centered cubic) occurs on cold-working.

The metal can be annealed at 980 to 1060°C. Thin sections can be air cooled; however, heavier parts should be water quenched. The metal after removal from the furnace should cool below 700°C in less than three minutes if the fine-grain annealed structure is required.

Ease of Outgassing:

The usual thin-wall parts will outgas readily at 1000°C in 15-30 minutes if previously fired in dry hydrogen. Vacuum firing before assembly is advantageous if parts are kept scrupulously clean.

Joining Methods:

The high electrical resistivity of stainless makes spot-welding one of the preferred methods of joining. Brazing with silver alloys or copper is also done in good vacuum or dry hydrogen, but may lead to difficulties in some circumstances because of the electrolytic couples formed, or because the braze metal is less resistant than the stainless steel. Parts should be stress-relieved before brazing and time at temperature made as short as possible. Parts may be pickled in a nitric-hydrochloric acid mixture before brazing. Those brazing alloys containing phosphorous, must be avoided to prevent embrittlement and phosphide eutectic formation.

STAINLESS STEEL

Oxidation:

The passive oxide coating on an 18-8 alloy serves as a protective barrier preventing access to the metal by corrosive agents. Although stainless steel may be buffed and polished to present an attractive metallic appearance, the oxide begins to reestablish itself as soon as the surface is exposed to air. When heated to about 400°C , the surface layer thickens and takes on the characteristic green chromic oxide color; firing in wet hydrogen at 1000 to 1100°C produces a similar effect. The chromic oxide film is quite tenacious and stable and is used to protect brazing jigs from melted alloys, to increase radiation from hot parts in vacuum, and to control the secondary emission ratio.

Corrosion rates may be substantially increased in the presence of chloride ions which tend to penetrate and remove the oxide surfaces. Exposure to sea water or salt air may have a pronounced effect on the life expectancy of stainless parts.

Typical Applications:

Anodes, grids, supports, brazing jigs and fixtures.

STAINLESS STEEL

Table 18

TYPE 304 STAINLESS STEEL DATA

		<u>Ref.</u>
Density	7.86 - 7.94 g/cc	16, p. 70
Lattice Type	Face-centered cubic	
Melting Range	1454 - 1499°C	16, p. 2
Tensile Strength	79,000 Psi	16, p. 72
Yield Strength	35,000 Psi	16, p. 72
Modulus of Elasticity	29×10^6 Psi (Annealed)	16, p. 2
Maximum Elongation	54%	16, p. 72
Thermal Conductivity	.04 cal/sec/cm/°C at 20°C	2, p. 42-44
Specific Heat	.12 cal/°C/g, (0 - 100°C)	16, p. 2
Linear Thermal Expansion	15.4×10^{-6} in/in/°C, 20° - 100°C 17.6×10^{-6} in/in/°C (20° - 500°C)	16, p. 70 16, p. 70
Electrical Resistivity	72.5×10^{-6} ohm-cm at 20°C	16, p. 71
Temp. Coefficient of Resistivity	$9.4 \times 10^{-4}/°C$ (20° - 500°C)	37
Curie Point	Nonmagnetic at room temp.	7, p. 648
Magnetic Permeability	1.02 at 200 H annealed	16, p. 2
Temp. for 10^{-5} mm Vapor Pressure	1105°C	73, p. 29

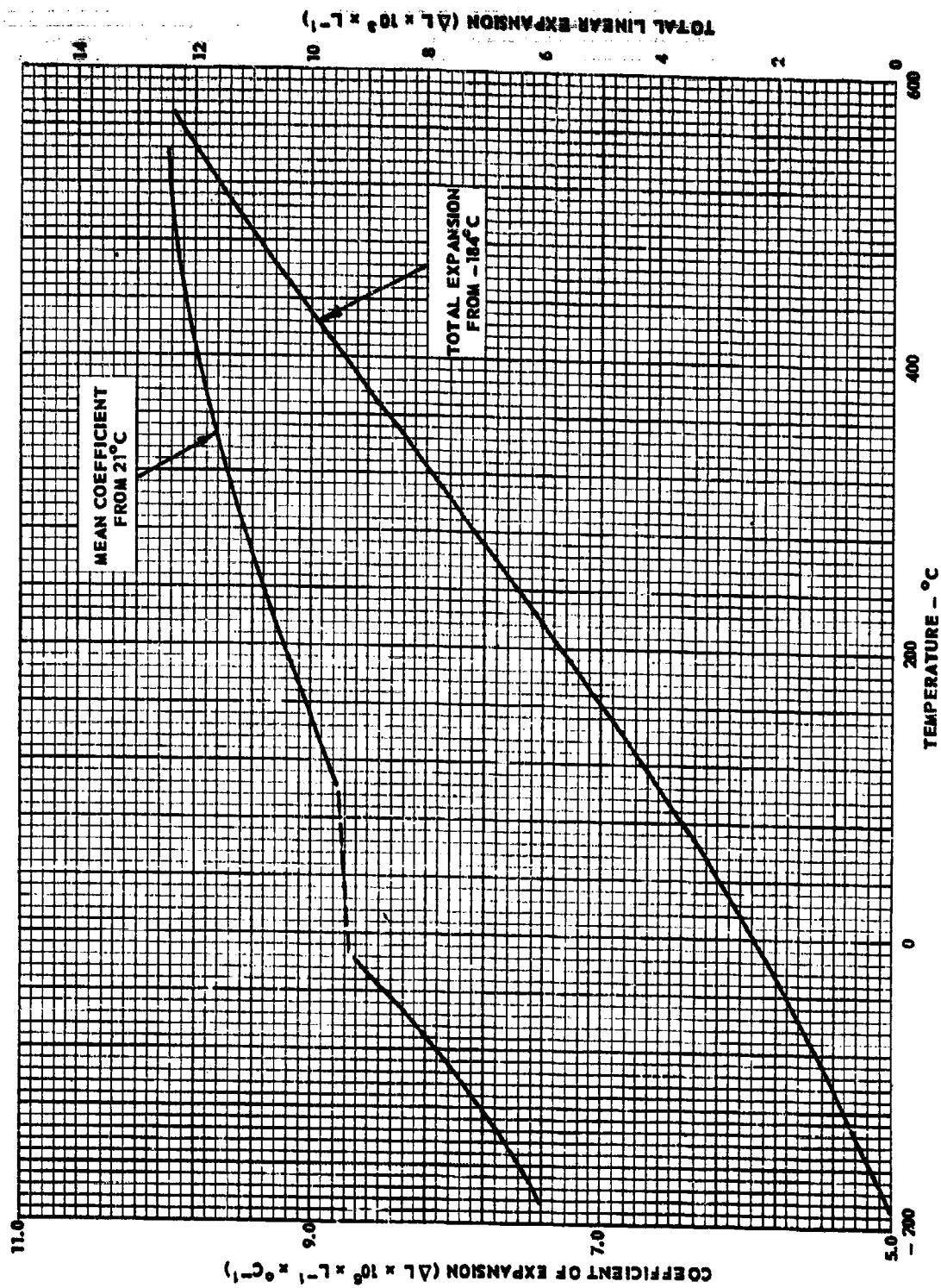


Fig. 64 — Linear Thermal Expansion and Mean Coefficient of Expansion for Type 304 Stainless Steel

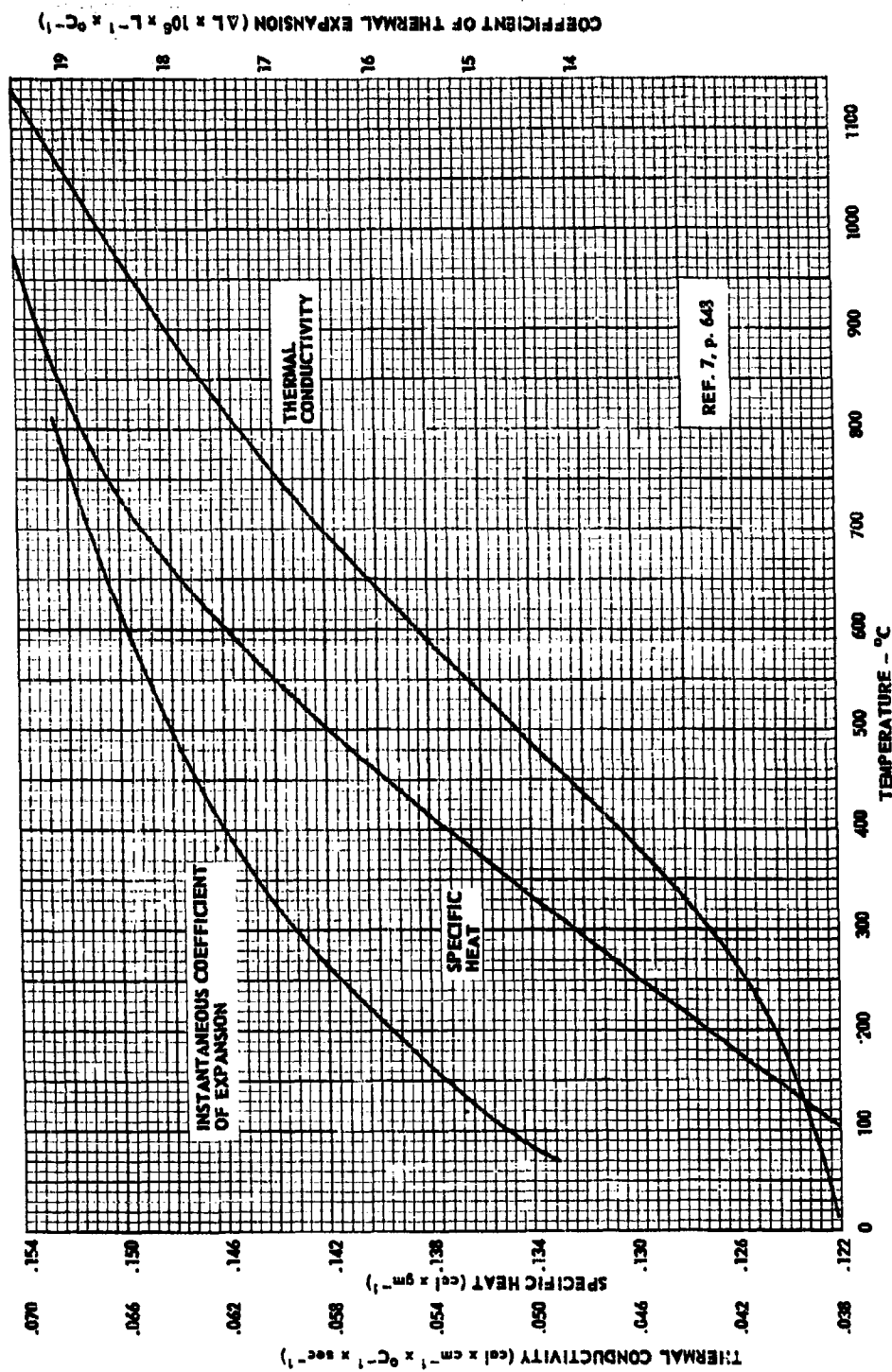


Fig. 65 -- Specific Heat, Thermal Conductivity and Instantaneous Expansion Coefficient for Type 304 Stainless Steel

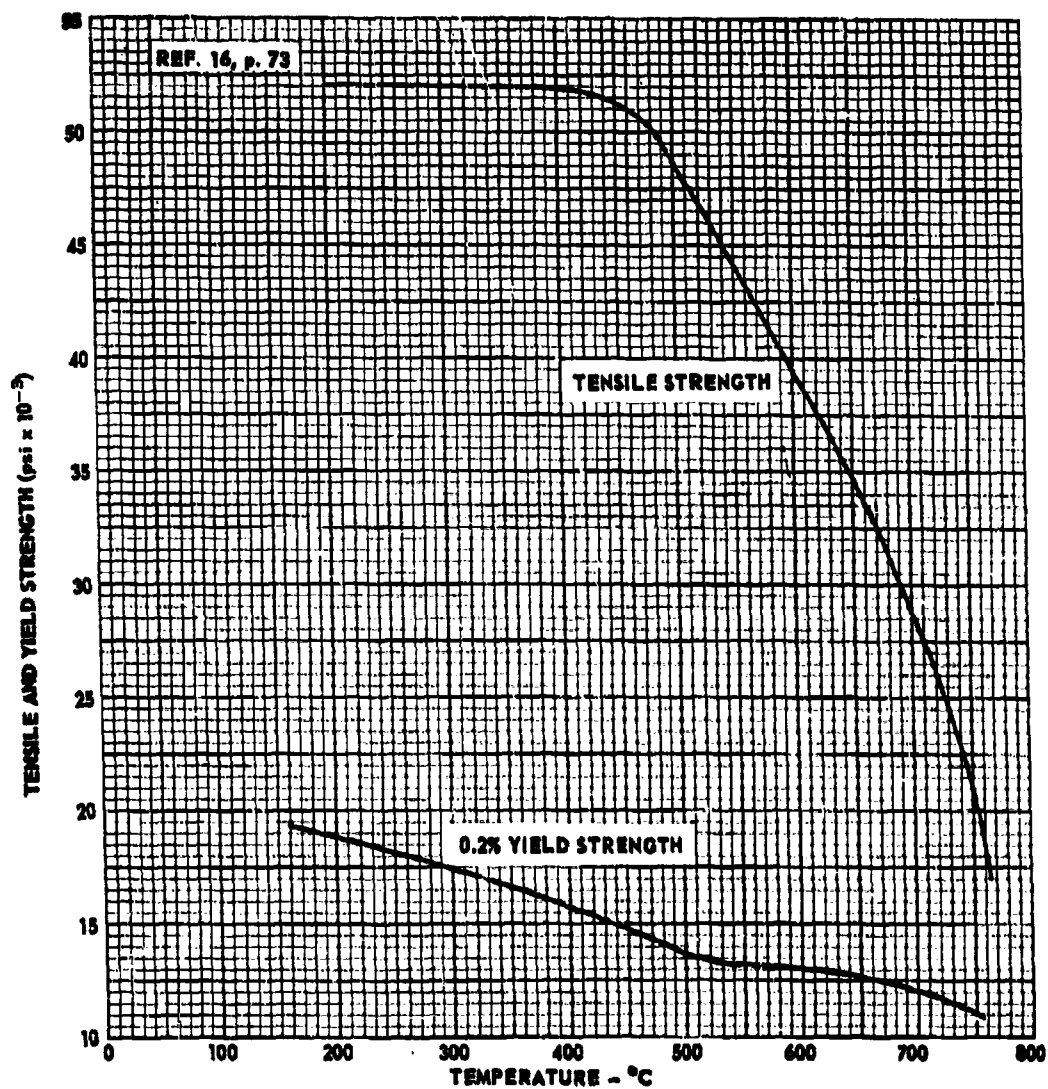


Fig. 66 — Tensile Strength and Yield Strength for Type 304 Stainless Steel

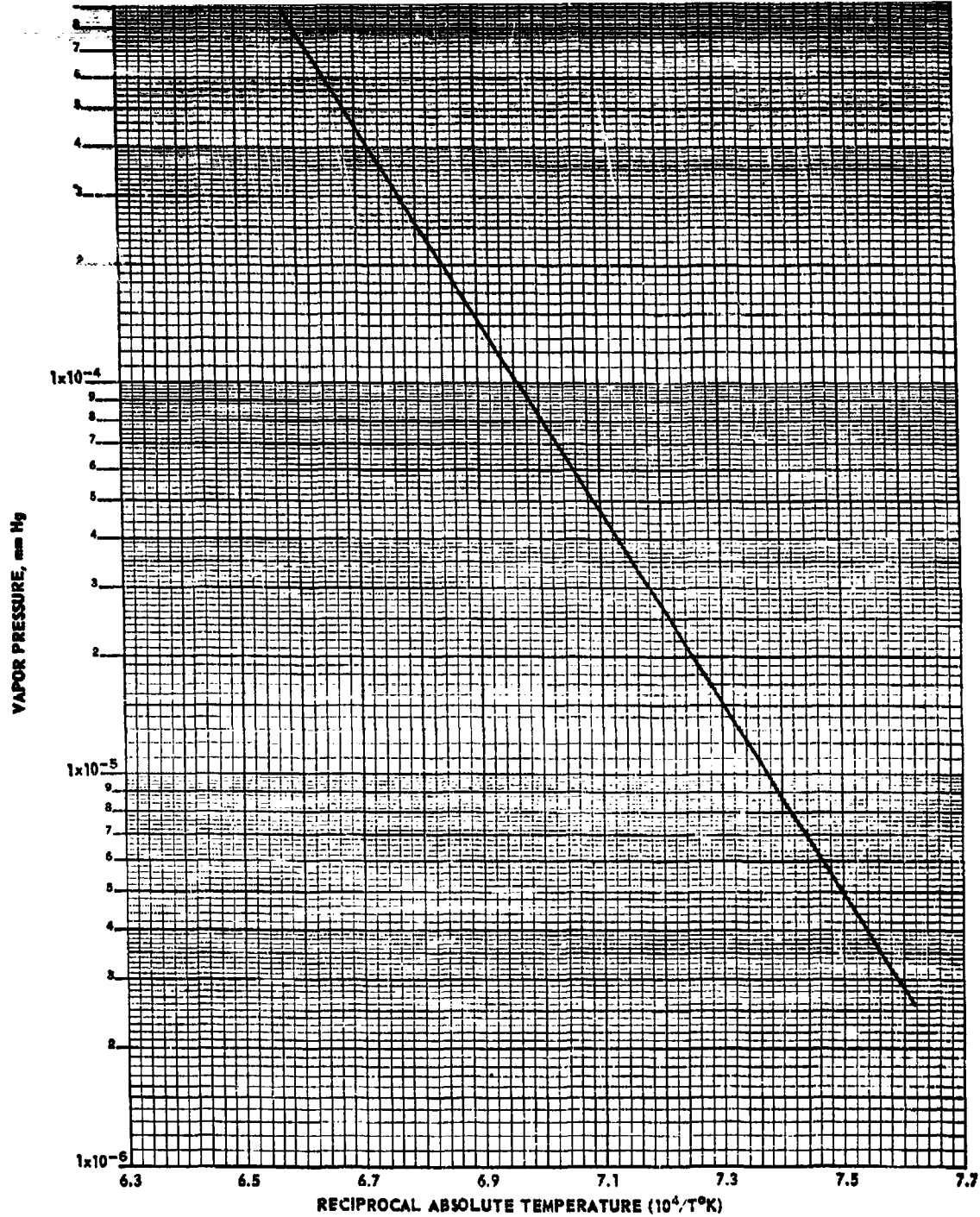


Fig. 67 — Vapor Pressure of Type 304 Stainless Steel

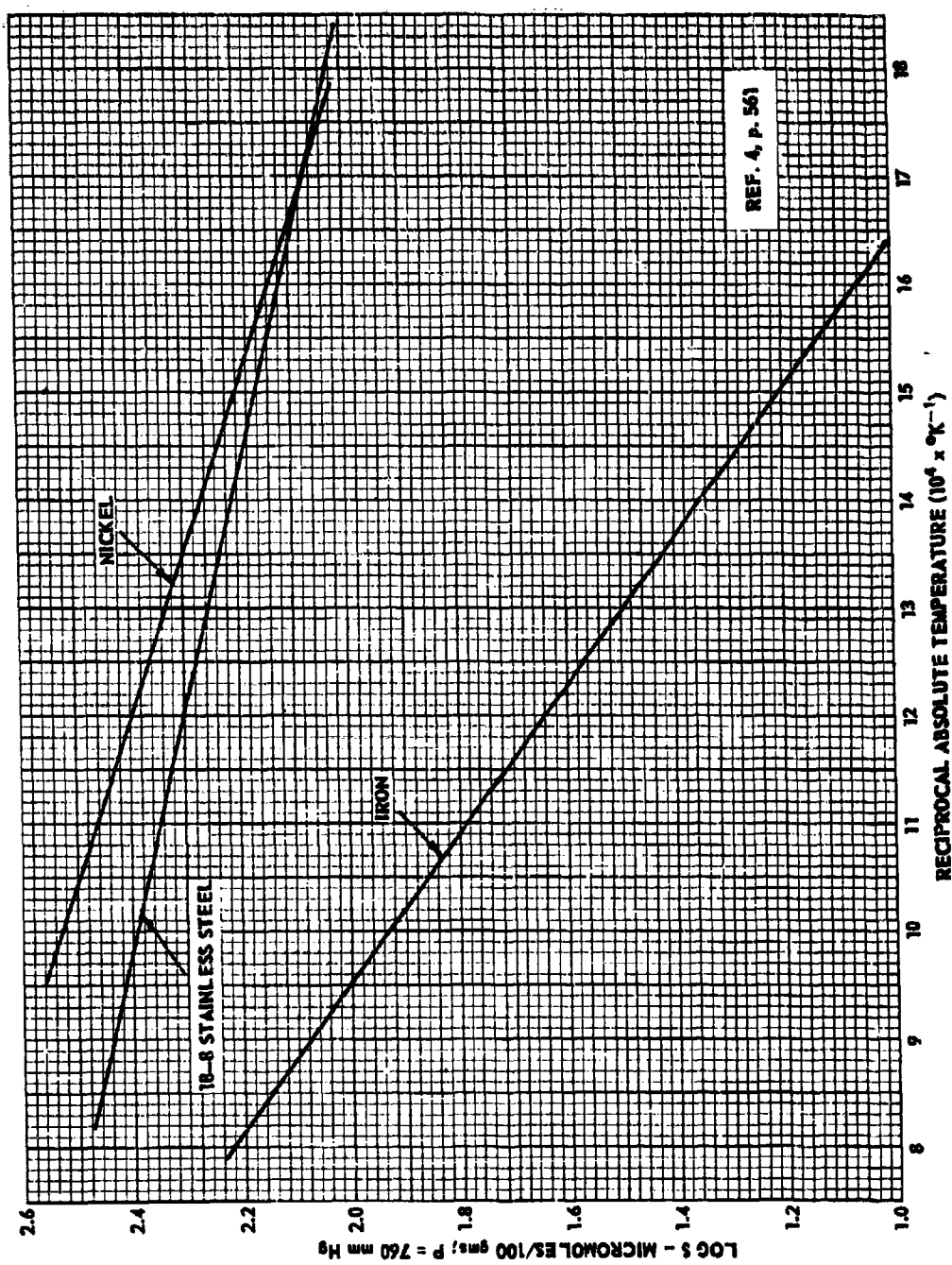


Fig. 68 -- Hydrogen Solubility in Type 304 Stainless Steel

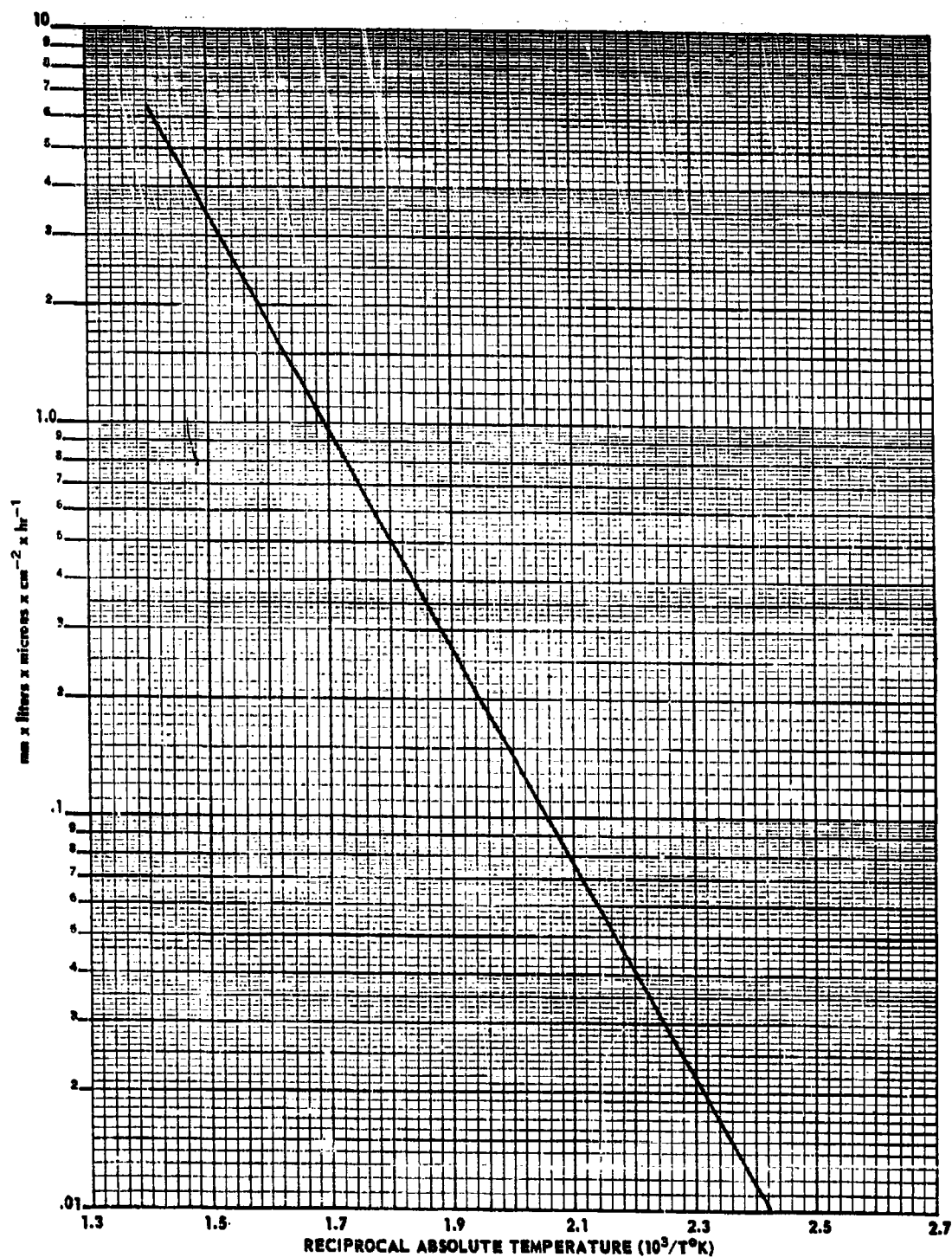


Fig. 69 — Hydrogen Permeation Through Type 304 Stainless Steel

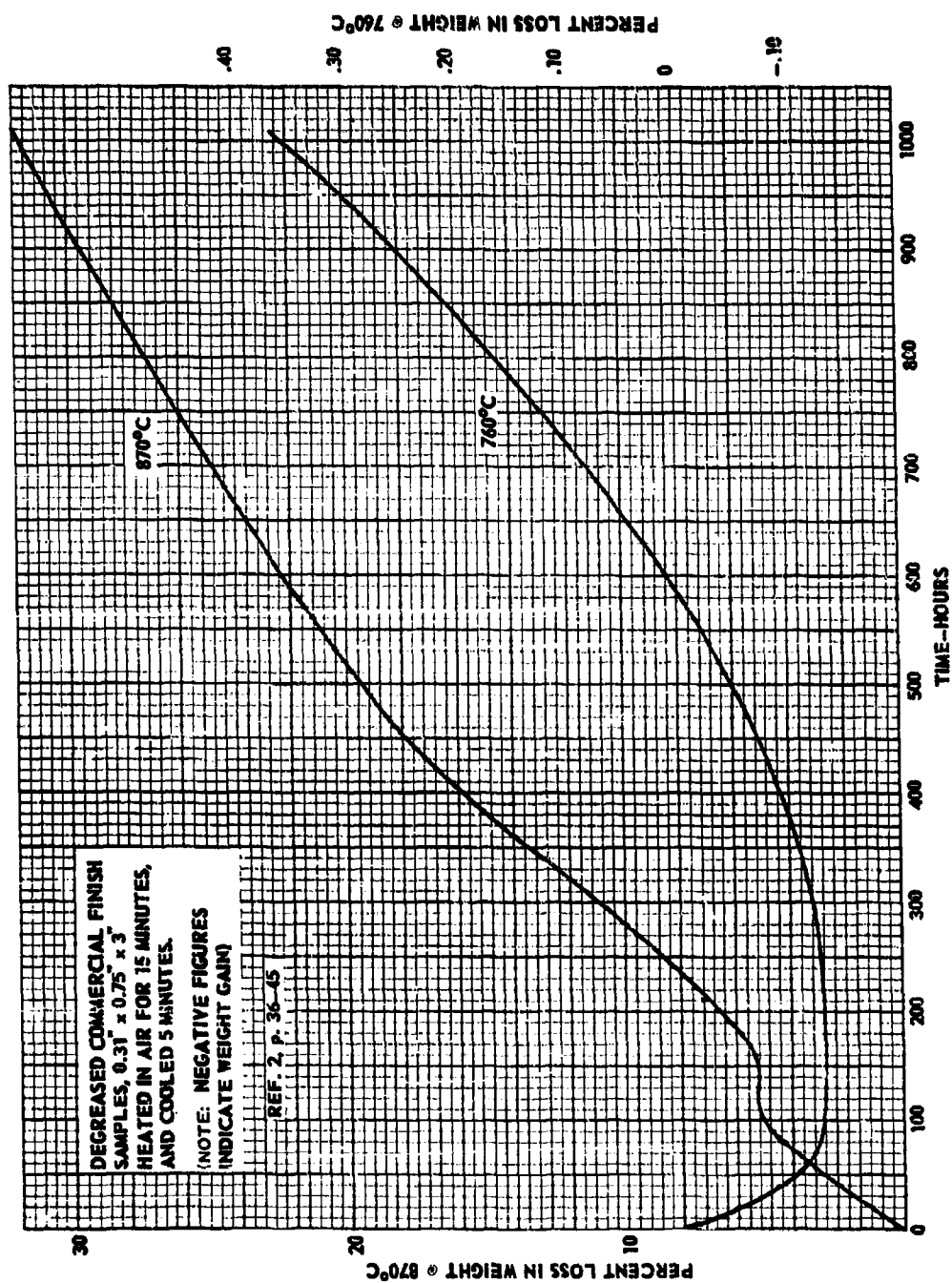


Fig. 70 -- Oxidation of Type 304 Stainless Steel

Material: Tantalum

Chemical Composition: 99.8% Tantalum

Trade Names and Numbers: Tantalum

Suppliers: Fansteel Metallurgical Corp., North Chicago, Illinois

Forms Available: Wire, tube, powder, bar, rod, foil. Sheet to $\frac{1}{4}$ " thick.

General:

Tantalum in the pure state is a blue-grey, malleable and ductile metal approximating soft steel in its physical characteristics. Small amounts of gaseous impurities (H_2 , N_2 , O_2) or carbon may make it brittle and difficult to fabricate. It is a member of group V-A of the periodic table, along with vanadium and columbium.

Joining:

Tantalum may be joined to itself and to other refractory metals by pulse welding or brazing. Air must be excluded by working under water or carbon tetrachloride, (for welding), or by working in a vacuum (for brazing.)

Special Handling Techniques and Formability:

Pure sheet material is easily spun, drawn and blanked at room temperature, but the metal is sufficiently reactive to preclude any sort of furnace annealing except under vacuum. Blanking tools preferably should be of cold rolled steel; tool steel is too hard and permits excessive slippage. Ordinary automotive cup grease makes a suitable lubricant but may present difficulties for tube applications unless completely removed. Tantalum shows gettering characteristics at about $700^{\circ}C$ after a $2000^{\circ}C$ outgassing.

This means that annealing should be performed at 10^{-6} mm Hg or lower; it is advisable to isolate the system from the pumps before cooling the tantalum so that no gases may be drawn back as the metal cools through its optimum absorption range.

A tantalum tube structure designed for operation at 600°C or higher should be supported by tantalum or tungsten, unless the supporting elements are kept reasonably cool. Tantalum will alloy readily with nickel at 600°C , causing distortion and warpage.

Allotropic Changes:

No allotropic or permanent dimensional changes are reported after annealing or outgassing; crystal growth is apparently no problem under these conditions.

Ease of Outgassing:

Must be heated to 2000°C , preferably higher in vacuum of $< 1 \times 10^{-6}$ mm Hg. Oxides evaporate at 1800°C , nitrides are stable to higher temperatures.

Applications:

Tantalum is used for cathodes, anodes, filaments and supporting structures. A semiconducting oxide film may be formed on tantalum by electro-chemical means. This film finds applications in condensers and rectifiers, especially where small size is important.

Oxidation:

Oxidation resistance in air is only fair for operation above 400°C . Carbon monoxide and nitrogen are absorbed at temperatures of 600°C and higher; hydrogen is absorbed at temperatures below 700°C . Water vapor rapidly attacks tantalum at 700°C .

TANTALUM

Table 19
TANTALUM DATA

		<u>Ref.</u>
Density	16.6 g/cc	5
Lattice Type	Body-centered cubic	5
Melting Temperature	2996 \pm 50°C	5
Tensile Strength	50,000 Psi (Annealed)	5
Modulus of Elasticity	27 $\times 10^6$ Psi	5
Maximum Elongation	40%	5
Thermal Conductivity	.130 cal/sec/cm/°C	5
Specific Heat	.036 cal/g/°C (0°C)	5
Linear Thermal Expansion	6.5 $\times 10^{-6}$ in/in/°C (0 - 500°C)	5
Emissivity Rate	20°C .49 930°C .45 at .665 μ 1730°C .42	46
Electrical Resistivity	12.4 $\times 10^{-6}$ ohm-cm at 20°C	5
Temp. Coefficient of Resistivity	38.2 $\times 10^{-4}$ /°C	5
Magnetic Susceptibility	0.93 $\times 10^{-6}$	
Electron Work Function	4.10 eV	5
Positive Ion Emission	10.0 eV	5
Temp. for 10^{-5} mm Vapor Pressure	2400°C	81

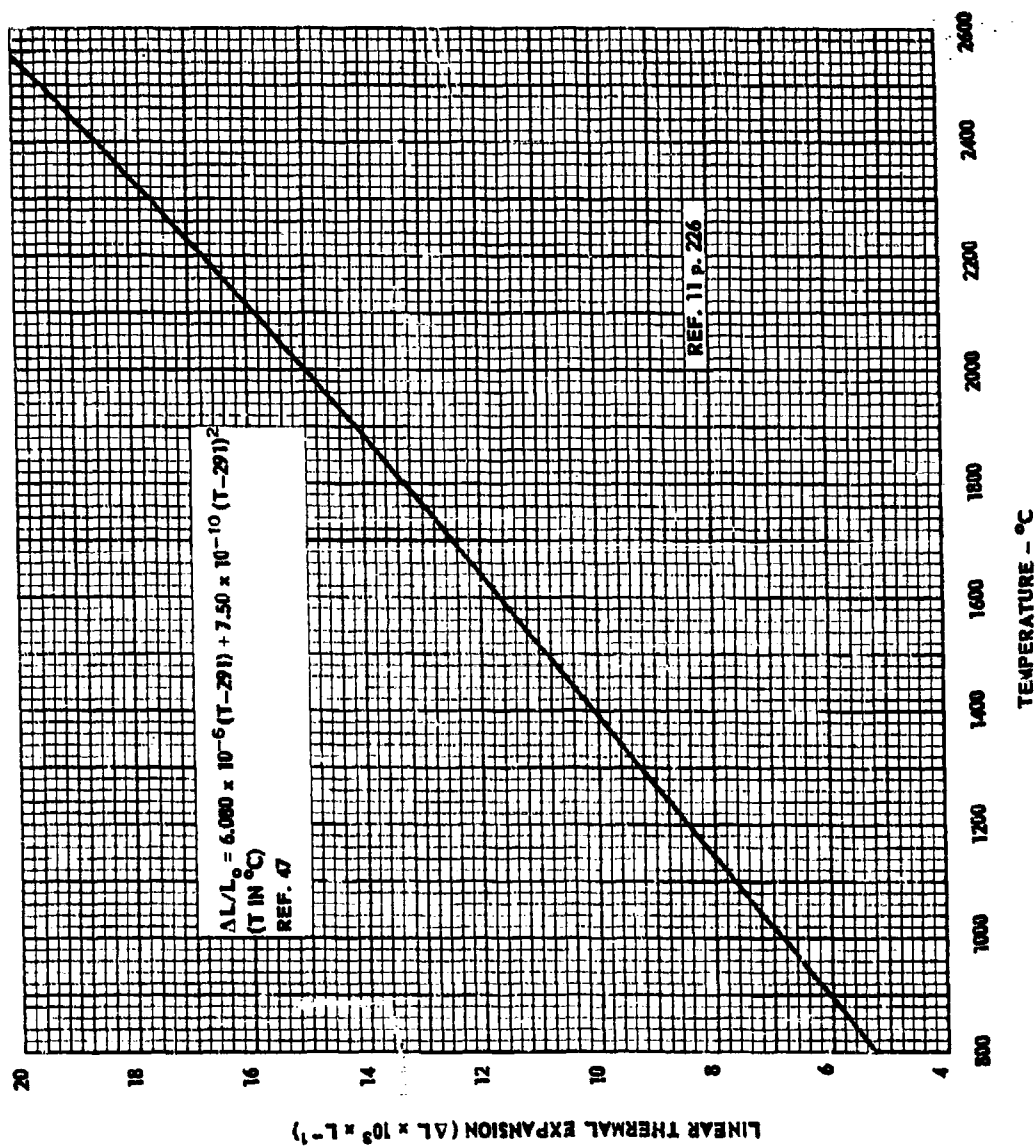


Fig. 71 — Linear Thermal Expansion of Tantalum

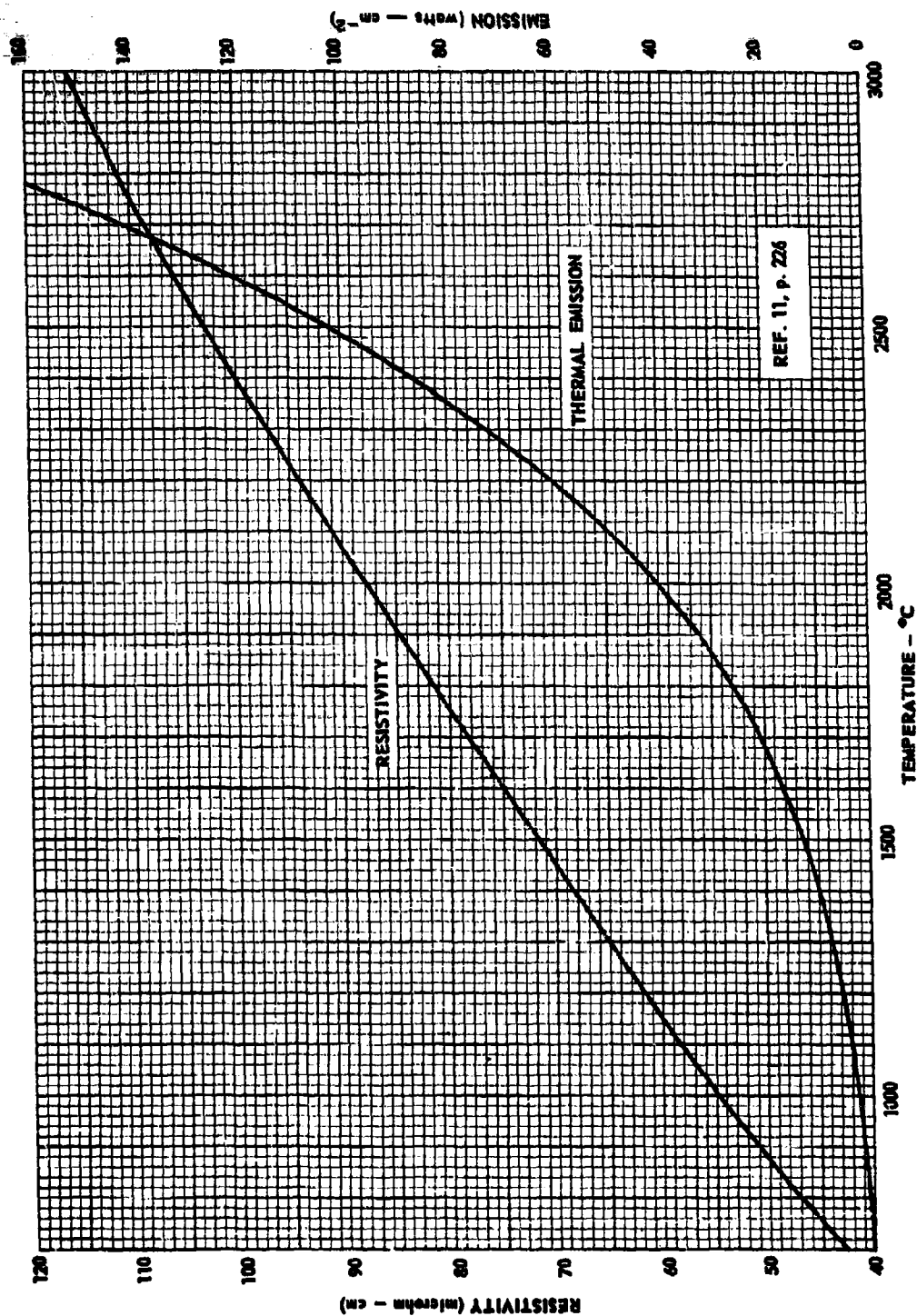


Fig. 72 -- Thermal Emission and Electrical Resistivity of Tantalum

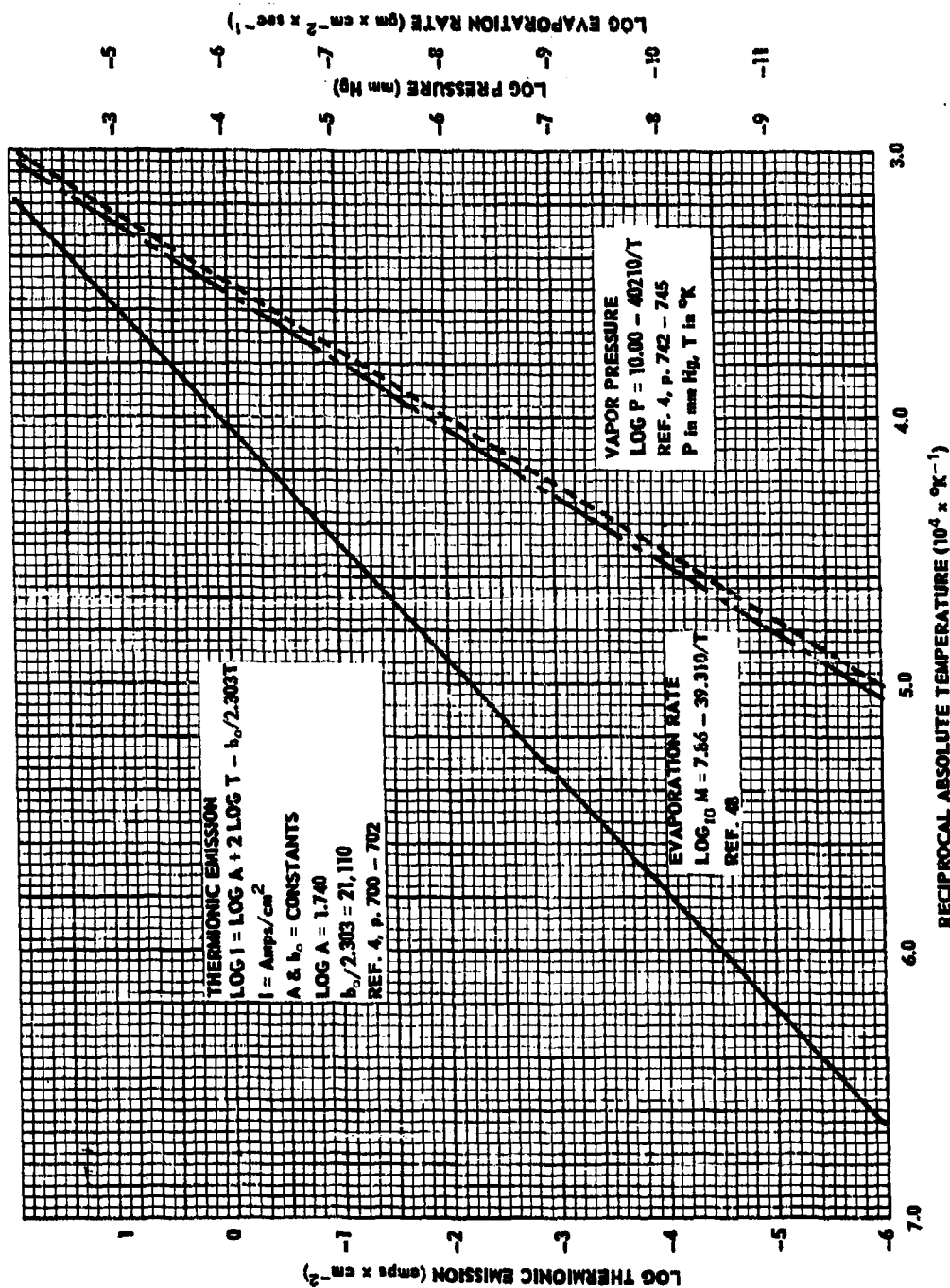


Fig. 73 — Vapor Pressure and Saturated Thermionic Emission vs. Reciprocal Temperature for Tantalum

Material: Titanium

Chemical Composition:

High Purity

Commercial Purity

99.9% min. Titanium

99.2% min.

Trade Designations: Titanium

Suppliers: Crucible Steel Co. of Amer., Mellon Sq., Pittsburgh 22, Pa.

Mallory-Sharon Metals Corp., 980 Warren Ave., Niles, Ohio

Republic Steel Corp., 3100 East 45th St., Cleveland 27, Ohio

Titanium Metals Co. of Amer., 233 Broadway, New York 7, N.Y.

National Distillers Prod. Co., 99 Park Ave., New York, N.Y.

U. S. Bureau of Mines, U. S. Dept. of Interior, Washington 25, D.C.

New Jersey Zinc Co., 160 Front St., New York 38, N.Y.

Foots Mineral Co., 452-18 West Chelton Ave., Philadelphia 44, Pa.

Harvey Aluminum Co., 19200 South Western Ave., Torrance, Calif.

Electro Metallurgical Co., 30 East 42nd St., New York 17, N.Y.

Forms Available: Bar, billet, plate, sheet, strip, tube, wire, extrusions

General:

Titanium is a silvery grey metal, a member of Group IV of the periodic table along with zirconium and hafnium. It combines light weight with high strength and excellent corrosion resistance at room temperature. It is nonmagnetic, has low thermal expansion, high electrical resistivity and low thermal conductivity. The pure unalloyed material is not recommended for applications under high stresses above about 400°C due to loss of strength and reaction with oxygen, nitrogen or hydrogen. High purity titanium is more ductile but not as strong as titanium which has been alloyed.

Special Handling Techniques and Formability:

The relative ease of machining titanium alloys is about proportional to their yield strength. Best results are obtained with the harder straight tungsten carbides. Tools should be kept sharp and not allowed to dwell in the cut.

Titanium has a low modulus of elasticity compared with steel.

Distortion may result when taking heavy cuts if large thin sections are not rigidly supported. Stress relieving prior to finish machining at 550°C is recommended where size is critical. Heat treatment must be carried out in vacuum or on inert atmosphere such as helium or argon.

When grinding titanium a fire hazard is caused by the production of fine chips or dust. Generous use of lubricants will lessen the danger of fire or explosion.

Pure titanium does not respond to heat treatment but may be hardened by cold-working. The hexagonal alpha structure of commercially pure titanium is the usual form encountered at room temperature. The addition of other elements regulate the transformation of hexagonal alpha to body-centered beta structure and utilizing these additions a variety of high strength alloys may be produced. This is more fully discussed under "Allotropic Changes".

When used for the construction of grids or other tube components, titanium offers marked advantages in some instances because of its very low primary emission and its resistance to activation by condensation of other materials, such as barium oxide, which have low work functions. Even

after oxidation (although emission rises considerably) titanium still shows much lower emission than most other tube materials, including even gold plated molybdenum. This has been demonstrated by Espersen and Rogers⁶¹.

Joining:

Titanium may be easily spot-welded but must be protected by welding under water or carbon tetrachloride. The metal is highly reactive toward oxygen and nitrogen, and pick-up of these elements causes embrittlement of the metal, particularly in the weld area.

Allotropic Changes:

Titanium occurs in two crystalline forms--alpha titanium which has a hexagonal close-packed structure and beta titanium which is a body-centered cubic. The alpha phase is stable from room temperature up to about 850°C, whereas beta is stable from this temperature to the melting point of 1720°C.

The addition of elements such as iron, chromium, manganese, molybdenum and vanadium lead to heat treatable alloys. In these alloys the transformation temperature is lowered and the beta phase is stabilized. Additions of aluminum tend to stabilize the alpha phase leading to higher strength at elevated temperatures, but these aluminum-titanium alloys cannot be heat treated to give high strength at room temperatures. Additions of tin or zirconium have little effect on the alpha-beta transformation.

Ease of Outgassing:

If titanium in the course of fabrication is exposed to nitrogen or oxygen while hot, it will pick up these elements forming extremely stable oxides or nitrides. These compounds will not decompose in any reasonable

TITANIUM

time on heating in vacuum. Hydrogen, however, may be removed at temperatures of about 1000° to 1100°C .

Applications:

Titanium may be used either as a bulk or flash getter. Another application of titanium is in getter-ion pumps as a continuously working getter. Titanium will braze directly to most ceramic materials in vacuum. It may be used for ceramic-metal seals in the elemental form, as an alloy constituent or as titanium hydride. At brazing temperatures the hydride decomposes to yield elemental titanium which dissolves in the brazing metal and wets the ceramic.

TITANIUM

Table 20
TITANIUM DATA

		<u>Ref.</u>
Density	4.55 g/cc	83
Lattice Type	Close-packed hexagonal	
Melting Temperature	1660°C - 1825°C	83
Annealing Temperature	450°C - 700°C	37
Tensile Strength	65,000 - 100,000 Psi	5
Yield Strength	45,000 - 85,000 Psi	5
Modulus of Elasticity	15.5 x 10 ⁶ Psi	5
Maximum Elongation	30%	5
Thermal Conductivity	0.41 cal/cm/sec/°C	5
Specific Heat	.139 cal/g/°C	5
Linear Thermal Expansion	8.5 x 10 ⁻⁶ in/in/°C (20° - 700°C)	5
Electrical Resistivity	47.8 x 10 ⁻⁶ ohm-cm	5
Temp. Coefficient of Resistivity	54 x 10 ⁻⁴ /°C	
Curie Point	Nonmagnetic	
Magnetic Permeability	1.0001	83
Temp. for 10 ⁻⁵ mm Vapor Pressure	1520°C	81

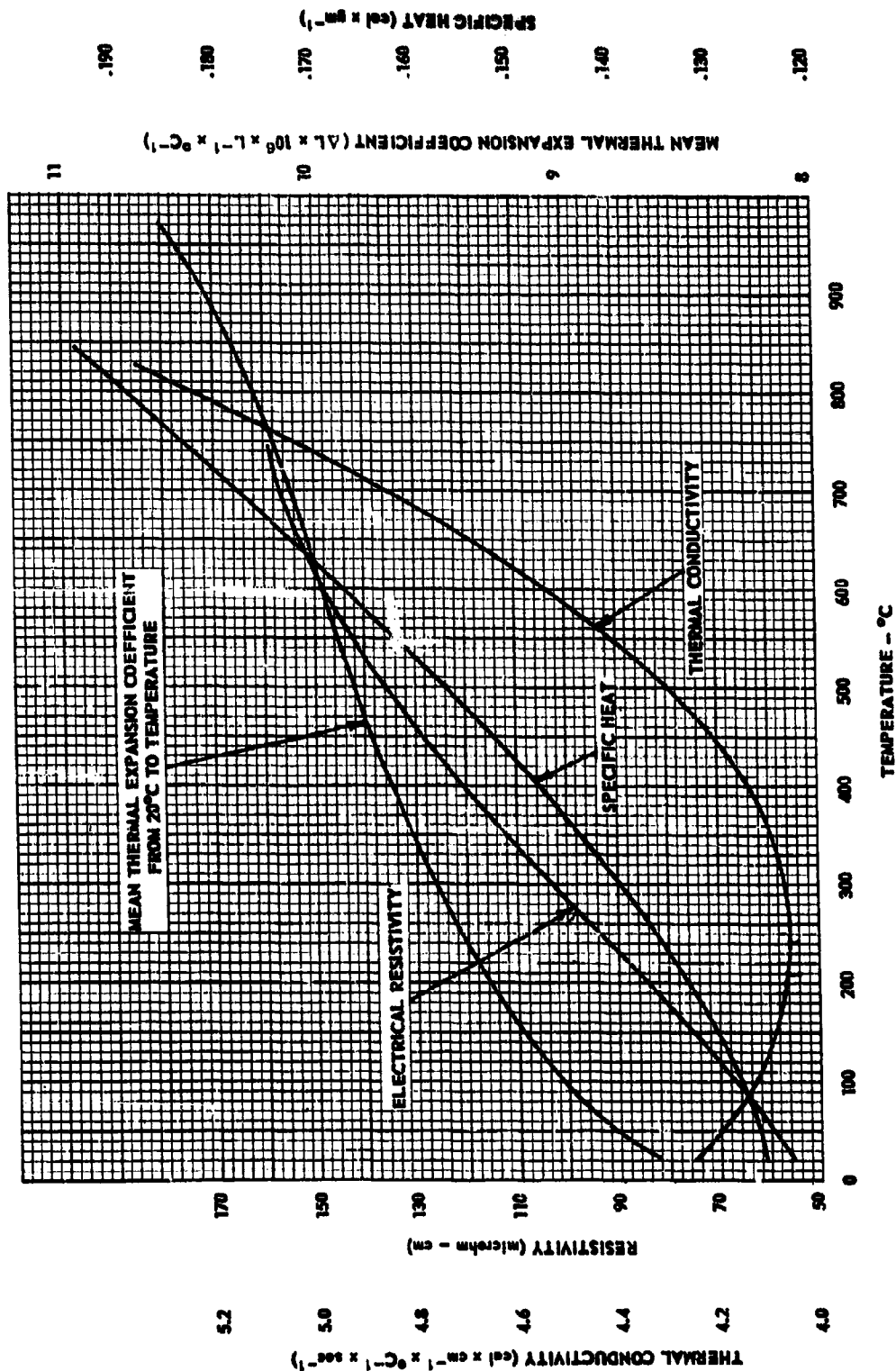


Fig. 74 — Electrical Resistivity, Specific Heat, Thermal Conductivity and Mean Coefficient of Thermal Expansion for Titanium

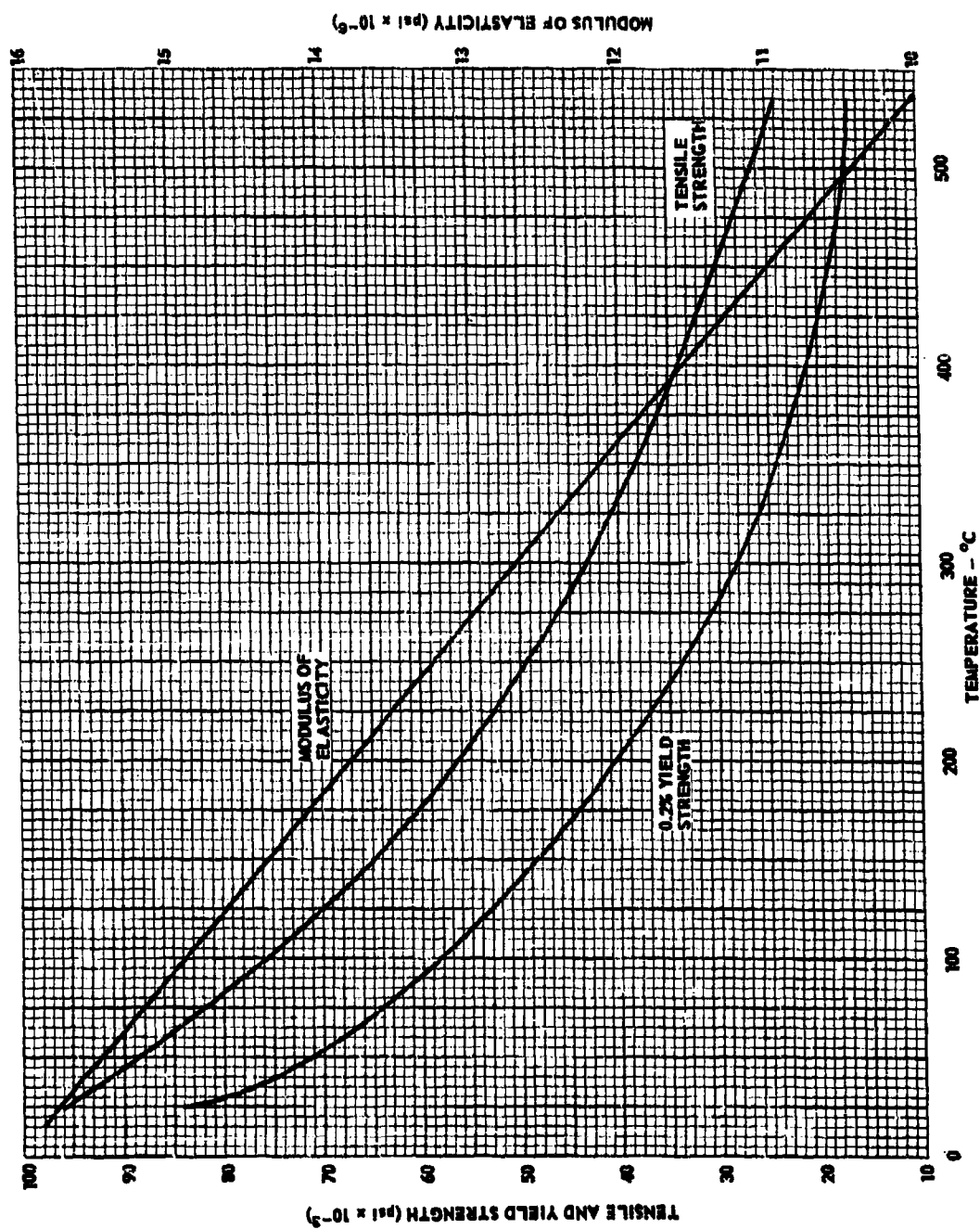


Fig. 75 — Mechanical Properties of Titanium

Material: Tungsten

Chemical Composition: More than 99% Tungsten

Trade Names and Numbers: Tungsten, Wolfram

Suppliers: Electro Metallurgical Co., Carbide & Carbon Bldg., 30 E. 42nd St.,
New York 17, N.Y.

Fansteel Metallurgical Corp., North Chicago, Illinois

Westinghouse Electric Corp., 101 Liberty Ave., Gateway Center,
Pittsburgh, Pa.

General Electric Co., Lamp Wires & Phosphors Dept.,
1331 Chardon Rd., Cleveland 17, Ohio

Sylvania Electric Products, Inc., 1740 Broadway, New York 19, N.Y.

Forms Available: Powder, bar, rod, wire, sheet and tube.

General:

Tungsten has many excellent properties to recommend it for vacuum tube work. It is the most refractory metal; the vapor pressure is reported to be lower than that of carbon. Tungsten is easy to outgas, has high strength at elevated temperatures and, among the common electron-tube structural materials, is second only to copper in its electrical conductivity. Its use is limited by two factors: cost and workability. New techniques now available promise to widen its use considerably. Slip-casting of complicated shapes has been shown to be practical, and the development of new and improved shop practices and controlled purity material have shown that tungsten can be drawn, spun and blanked. Deep drawn and complicated shapes are commercially available.*

*Fansteel Metallurgical Co., North Chicago, Illinois

Joining:

Tungsten may be brazed in hydrogen or vacuum using copper, nickel, platinum or commercial brazing alloys such as Nicro, Nicoro and Wesgo alloys.

Tungsten may be pulse welded to itself or other metals by using a thin tab of nickel or tantalum in the joint. If tantalum is used, the weld should be made under water or carbon tetrachloride.

Special Handling Techniques and Formability:

Commercially pure tungsten, hydrogen-reduced for electronic work, may be handled somewhat like molybdenum. Heavy sections must be worked hot, but continued working leads to smaller grain size and greater ductility. One major difference between tungsten and the more common structural metals is that tungsten crystals are stronger than the crystal boundaries and tensile failure is always intercrystalline as opposed to the normal type of transcrystalline fracture. Thus completely annealed tungsten (large grain) is extremely brittle at room temperature and cannot be formed or bent without cracking and breaking between the grains. Some tungsten will be lost through oxidation during swaging, annealing, drawing and rolling to useful size and shape. This has been known to be as high as 15%.

Allotropic Changes:

There are no allotropic changes on heating or cooling.

Ease of Outgassing:

Oxygen and nitrogen may be removed by outgassing either in a hydrogen atmosphere or in a vacuum at 800 - 1000°C for 10 - 30 minutes. Tungsten

parts which are made from wire or thin sheet stock, can be outgassed quite easily if the metal can be heated to 1000°C or more during processing. This can usually be done by resistance heating, electron bombardment, or induction heating.

Applications:

Tungsten is often used for leads through Nonex glass where its low resistivity favors its use instead of Kovar, and where the advantage of using tungsten in all-pyrex system may offset the lower cost of Kovar.

Thoriated tungsten is used directly as a cathode material, and the pure wire is commonly used as an indirect heater for cathodes. Admixtures of up to 2% thoria exert considerable influence in retarding grain growth and extending the life of hot filaments. At temperatures above 2700°K, thoria is reduced by metallic tungsten. After flashing for a minute or two at this temperature, the filament is allowed to cool to about 2100°K and held at this temperature for a few minutes to permit diffusion of metallic thorium to the surface. Activation may be monitored by drawing emission current from the wire. After a steady state is reached, the temperature should be lowered to about 1600 - 1700°K; this permits an equilibrium to be established whereby the diffusion of thorium to the surface just equals the evaporation (both being low values) and a low work-function surface is sustained for long-term continuous emission. The vacuum should be kept to about 10^{-6} mm Hg or less for satisfactory cathode performance.

TUNGSTEN

Table 21

TUNGSTEN DATA

		<u>Ref.</u>
Density	19.3 g/cc at 20°C	2
Lattice Type	Body-centered cubic	8
Melting Point	3410°C	2
Tensile Strength	225,000 - 300,000 Psi (wire)	5
Modulus of Elasticity	60×10^6 Psi	2
Maximum Elongation	0%	5
Thermal Conductivity	.31 cal/cm/sec/°C at 20°C	5
Specific Heat	.034 cal/gm/°C (20°C)	5
Linear Thermal Expansion	4.82×10^{-6} /°C, 30 - 1000°C	1, p. 57
Spectral Emissivity	at .665 μ at .650 μ	7
	20°C .470 .453	
	900°C .452 .444	
	1700°C - .436	
	1900°C .431 -	
	2900°C .411	
Electrical Resistivity	5.48×10^{-6} ohm-cm	5
Temp. Coefficient of Resistivity	48.2×10^{-4} /°C (20° - 100°C)	5
Magnetic Susceptibility	0.28×10^{-6}	7
Electron Work Function	4.55 eV	5
Positive Ion Emission	11.93 eV	5
Vapor Pressure	1×10^{-5} mm Hg at 2570°C	81

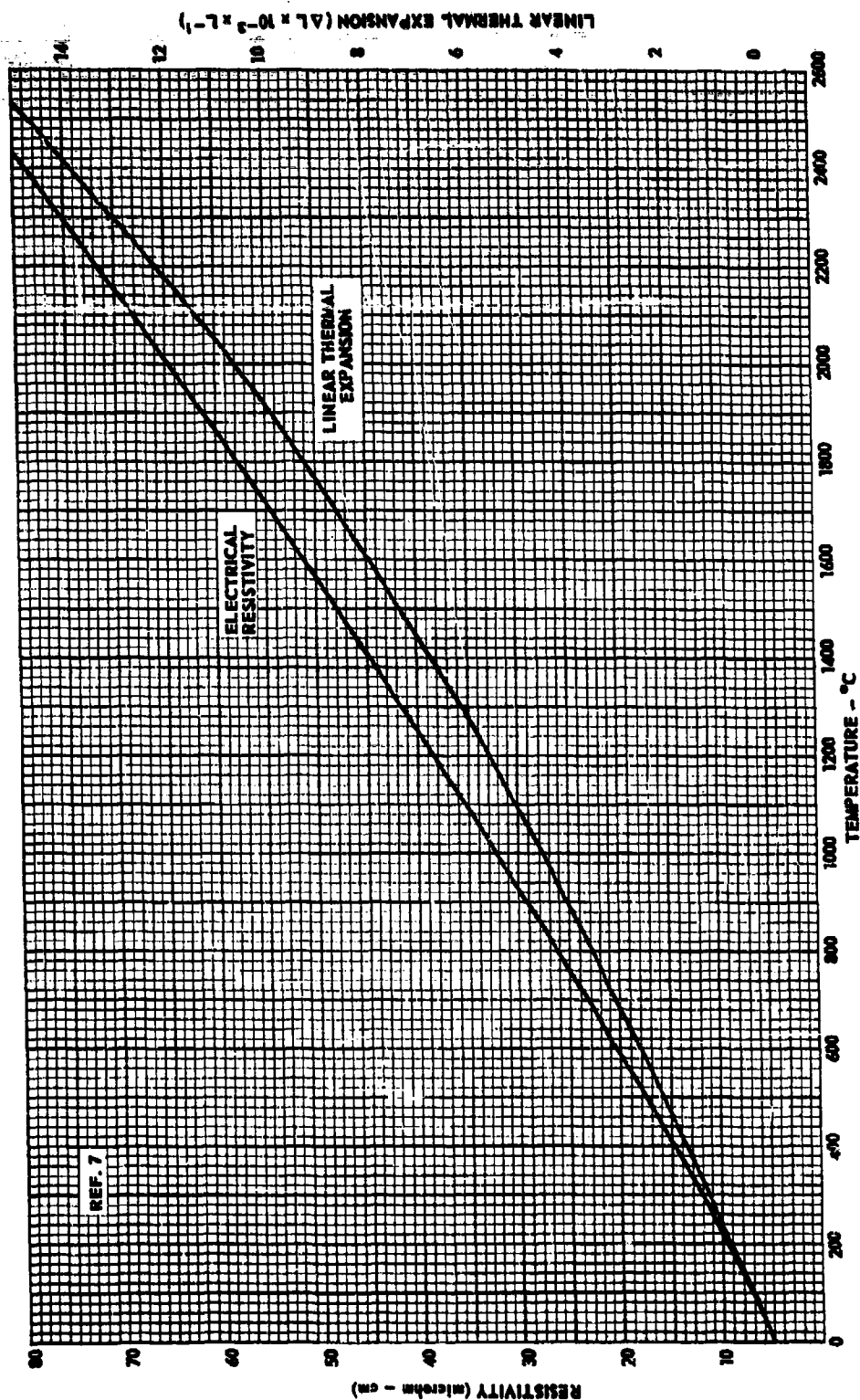


Fig. 76 -- Electrical Resistivity and Linear Thermal Expansion of Tungsten

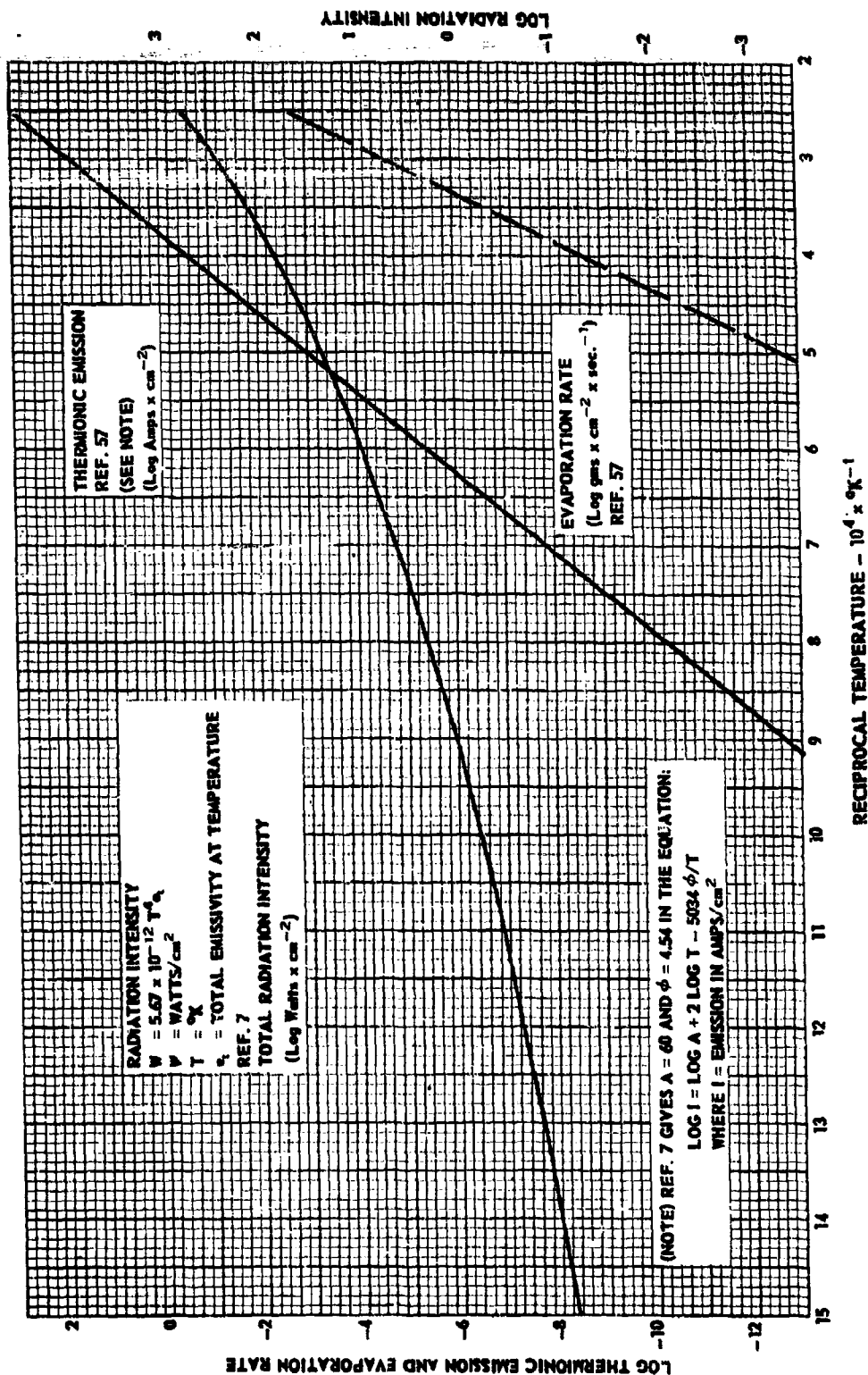


Fig. 77 — Thermionic Emission, Thermal Emission and Evaporation Rate of Tungsten

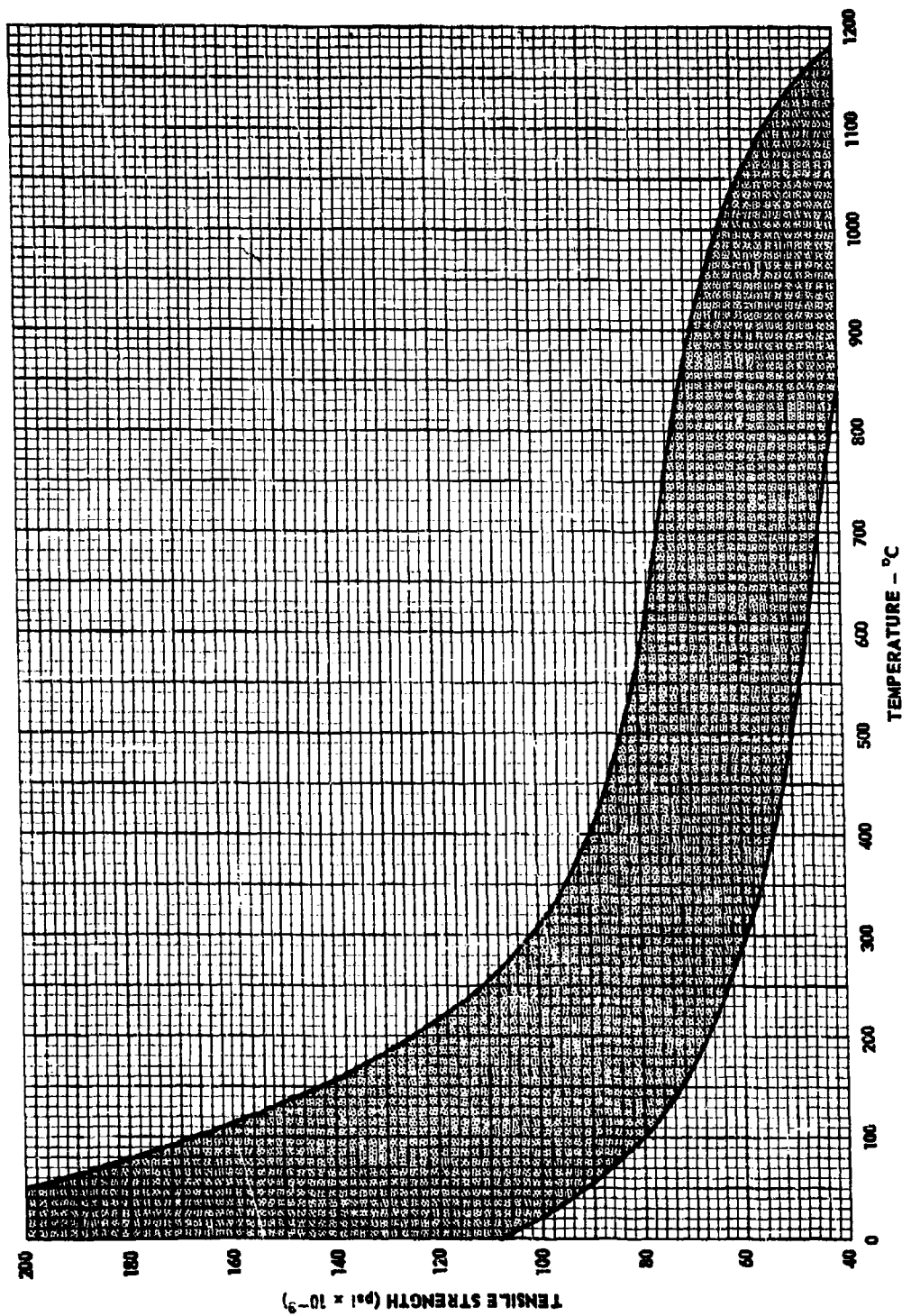


Fig. 78 -- Tensile Strength of Tungsten

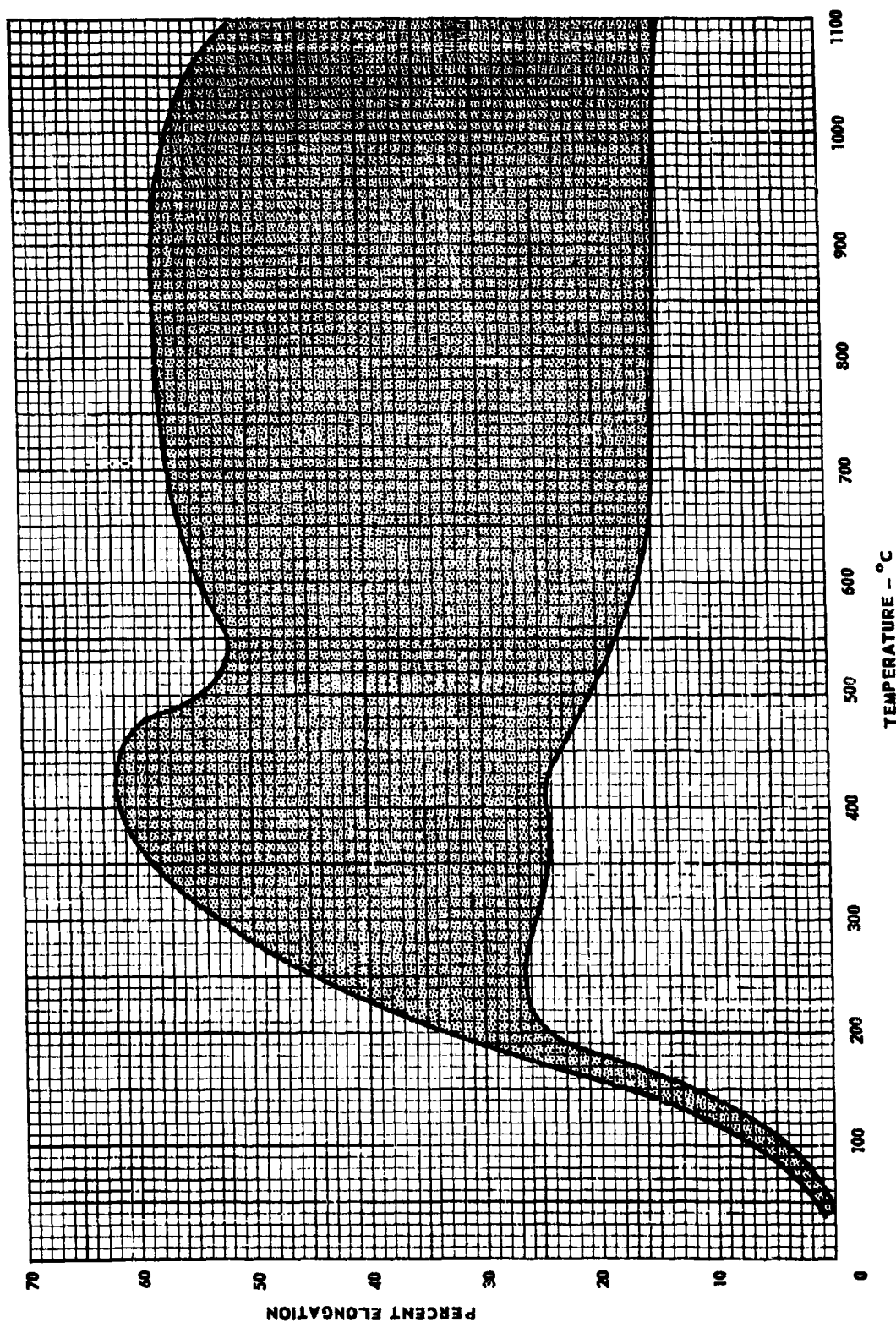


Fig. 79 — Percent Elongation of Tungsten

Material: Zirconium

Chemical Composition (%) :

<u>Reactor Grade</u>		<u>Commercial Grade</u>	
Zirconium	- 99.5 Minimum	Zirconium + Hafnium	- 99.5 Minimum
Carbon	- 0.05	Hafnium	- 2.0 nominal
Iron	- 0.15	Iron	- 0.2
Chromium	- 0.02	Carbon	- 0.05
Hafnium	- 0.02	Aluminum	- 0.03
Manganese - 0.04			
All Others- Less than 0.02			

Trade Designations: Reactor Grade Zirconium

Commercial Grade Zirconium

Suppliers: The Carborundum Metals Co., Inc., Akron, N.Y.

Columbia-National Corp., Cambridge, Mass.

Foot Mineral Co., Philadelphia, Pa.

Harvey Aluminum Co., Torrance, Calif.

Mallory-Sharon Metals Corp., Niles, Ohio

Forms Available: Bar, rod, wire, tube, sponge, forgings, plate, sheet, strip.

General:

Zirconium has recently become available in relatively large quantities because of its potential in the atomic energy and aircraft fields. The metal is ductile, easily machined and corrosion resistant. It is anticipated that this metal will find wide use in the electronic industry.

Special Handling Techniques and Formability:

Zirconium may not be melted in air because of its extremely high affinity for nitrogen and oxygen. It begins to react at about 600°C, forming hard, abrasive film on the surface. This film may be removed by sand blasting or other mechanical methods followed by pickling in 50-50 mixture of water and nitric acid containing about 5% hydrofluoric acid. If zirconium is to be heated to 500°C or higher, vacuum firing at pressures less than 10^{-6} mm Hg is recommended. If this procedure cannot be followed, it may be possible to heat the material in a very dry hydrogen atmosphere and follow with vacuum annealing.

Zirconium also reacts with hydrogen but this absorbed hydrogen may be driven off again upon reheating in vacuum. The metal is quite brittle and fragile after absorbing hydrogen.

Because of its extreme reactivity and its low coefficient of expansion, zirconium may be sealed directly to ceramics or some glasses. Also it can be used as an intermediate member between ceramics or glasses and any other metal desired.

Zirconium work hardens quite rapidly, during machining or other deforming operations; however, even at 90% reduction, the Brinell hardness rises only to about 250. This is not too hard for further working.

Tube drawing is possible but lubrication presents a problem. In general, if the material is first plated or clad with copper it may be drawn using standard lubricants; otherwise, it is necessary to form an oxide film in order to retain oil or water soluble lubricants. The

presence of this film is undesirable because of its extreme hardness and abrasive action. Like titanium, zirconium is pyrophoric when in the finely divided state and special precautions should be taken in machining.

Joining:

Zirconium may be welded, brazed or soldered, but the joints must be protected from the atmosphere while hot.

Silver or copper may be used for brazing but the amount of brazing metal must be controlled by using preforms or shims. Vacuum-brazing is recommended. Zirconium may also be drilled, tapped or punched and mechanical fastening devices may be used.

Allotropic Changes:

Alpha zirconium (hexagonal close-packed) is the stable structure between room temperature and 862°C . The body centered cubic beta form is stable from this temperature to the melting point. Oxygen and nitrogen raise the transition temperature whereas hydrogen lowers it. The effects of alloying on the transition temperature have not yet been fully explored.

Ease of Outgassing:

Zirconium in the temperature range above 350°C is an extremely active scavenger for gases; it makes an excellent getter. If the metal is heated in air at temperatures high enough to form oxides or nitrides and later heated in vacuum these compounds will not break down. Oxygen and nitrogen are held tenaciously even in the molten metal.

Hydrogen, however, may be driven off at about 800°C . In fact, zirconium hydride is used as a brazing compound for ceramic-metal seals

ZIRCONIUM

because the hydride decomposes upon heating in vacuum to yield pure zirconium metal which will react with both ceramic and metal, forming vacuum-tight seals.

Applications:

The widest applications of zirconium in the electronic industry today are in getters and brazing materials.

It is quite possible, however, to build other tube components out of zirconium since normal machine shop fabrication techniques may be used. The excellent gettering properties of the metal offers an additional bonus when it is used in an application where it is heated in the tube. Zirconium has also been used as coatings on magnetron cathode end-hats to suppress end-hat emission which is detrimental to tube performance.

ZIRCONIUM

Table 22

ZIRCONIUM DATA

		<u>Ref.</u>
Density	6.5 g/cc	5, 84
Lattice Type	Close-packed hexagonal	5
Melting Temperature	1830 \pm 40°C	84
Transition Temperature	HCP to BCC 863 \pm 3°C	5
Tensile Strength	65,000 Psi (Room Temperature) 6,600 Psi (800°C)	5
Yield Strength	14,850 Psi	5
Modulus of Elasticity	11.3 $\times 10^6$ Psi	5, 84
Maximum Elongation	23.7%	5
Thermal Conductivity	.040 cal/cm/sec/°C	5, 84
Specific Heat	.068 cal/gm °C	5, 84
Linear Thermal Expansion	5.2 $\times 10^{-6}$ in/in/°C (0 - 600°C)	5
Electrical Resistivity	39.8 $\times 10^{-6}$ ohm-cm	84
Temp. Coefficient of Resistivity	44 $\times 10^{-4}$ /°C	5, 84
Curie Point	Nonmagnetic	5
Magnetic Permeability	1.3	5
Electron Work Function	4.13 eV	50, 5
Richardson Constant 'A'	330	50
Temp. for 10 ⁻⁵ mm Vapor Pressure	1840°C	81

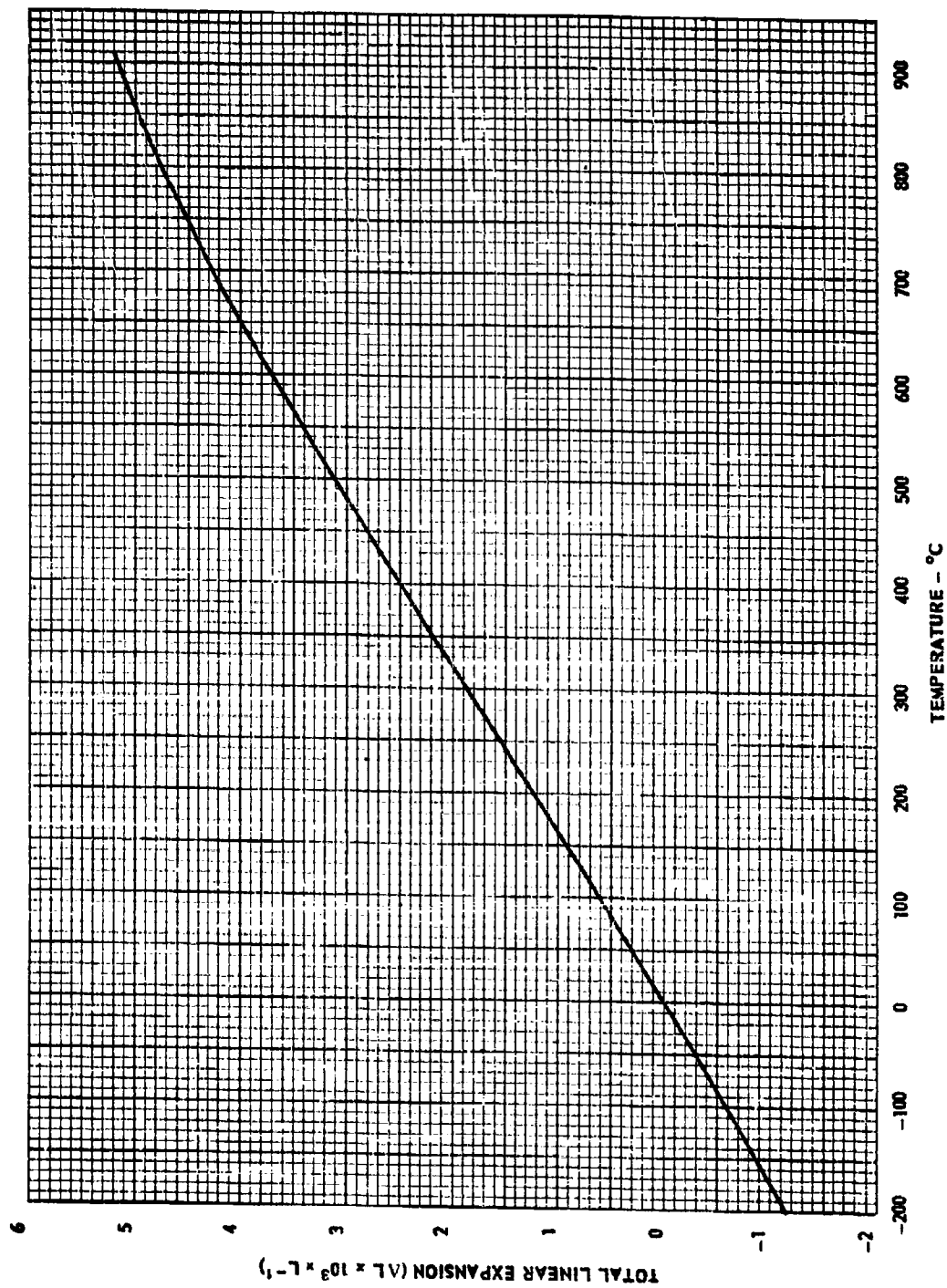


Fig. 80 — Linear Thermal Expansion of Zirconium

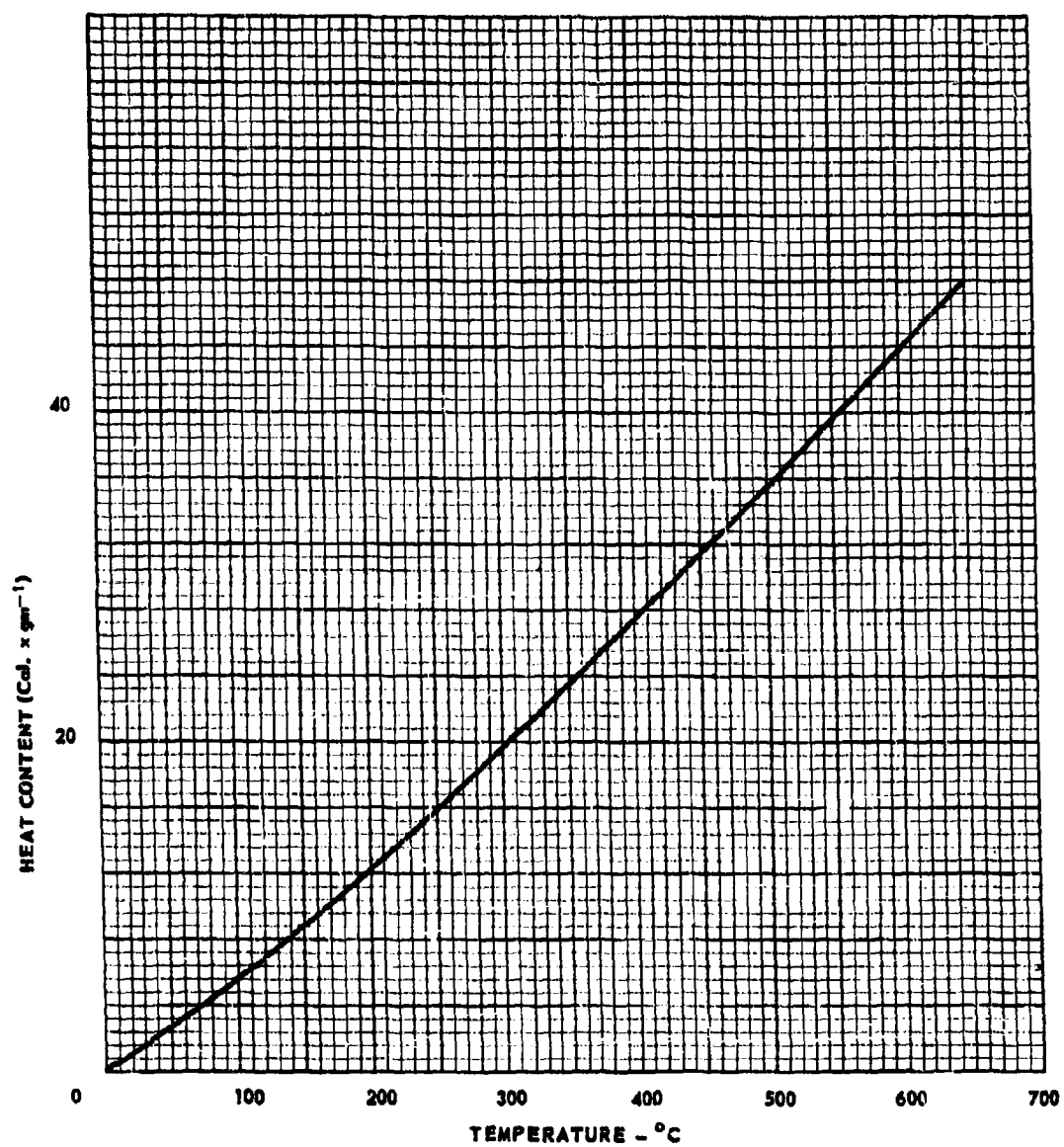


Fig. 81 — Heat Content of Zirconium

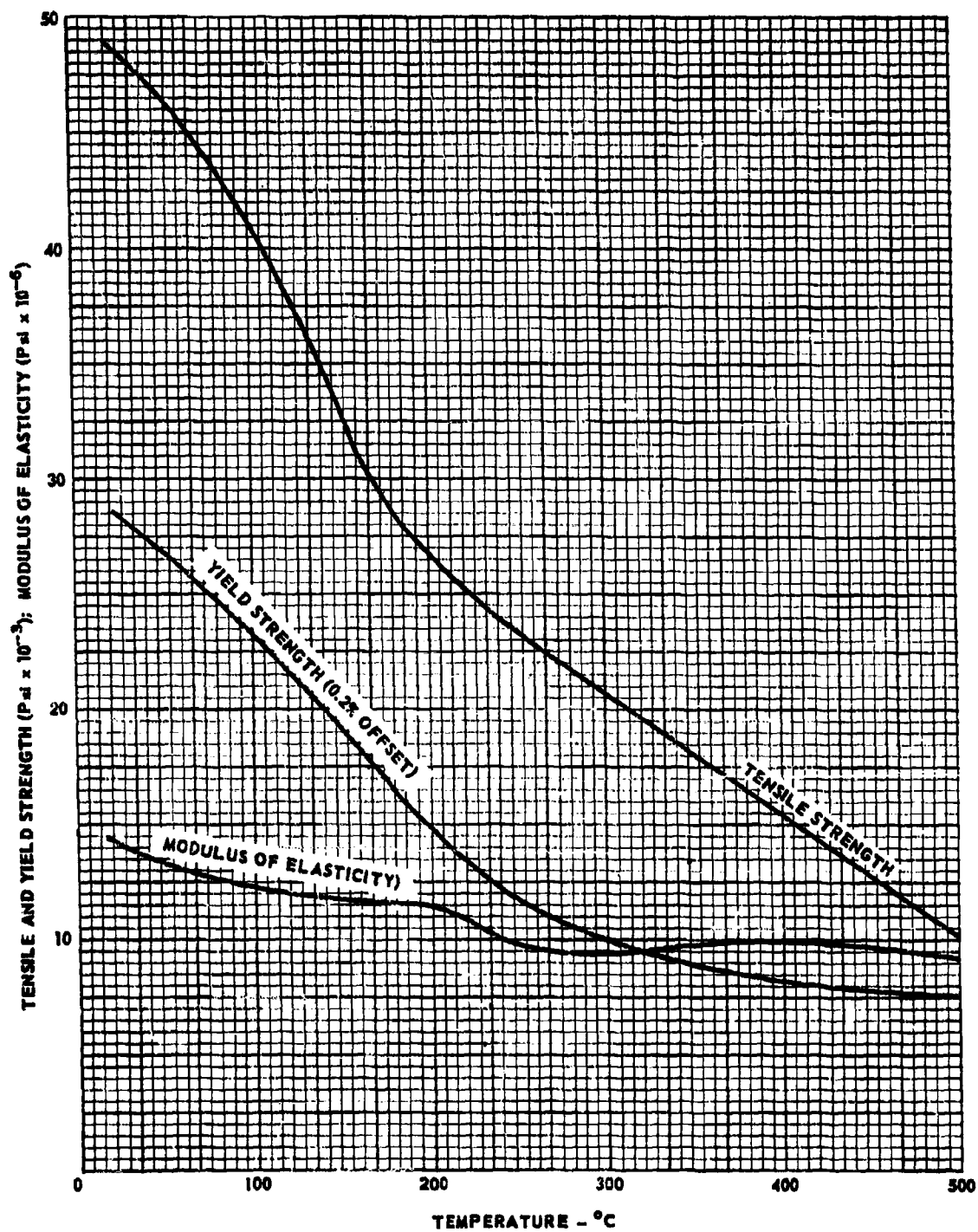


Fig. 82 — Mechanical Properties of Zirconium

SECTION IV

DATA BY PROPERTY

In this section data are tabulated and grouped for each property.
The following properties are included:

Thermal Expansion Coefficient

Thermal Conductivity

Density

Modulus of Elasticity

Melting Point

Specific Heat (mean)

Tensile Strength

Yield Strength

Electrical Resistivity

Thermionic Emission

Vapor Pressure

Evaporation Rate

Hydrogen Permeation

Hardness

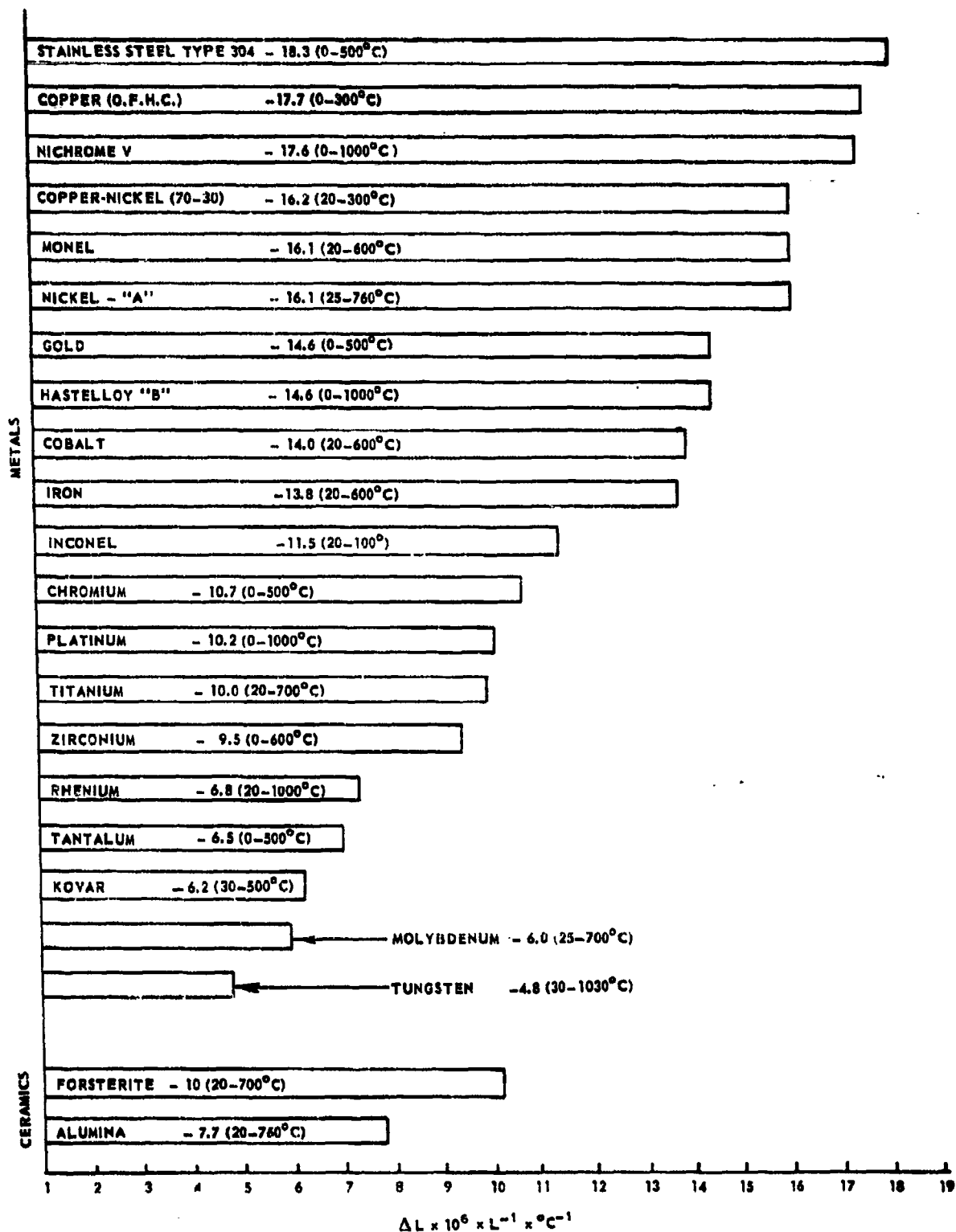


Fig. 83 — Coefficient of Thermal Expansion

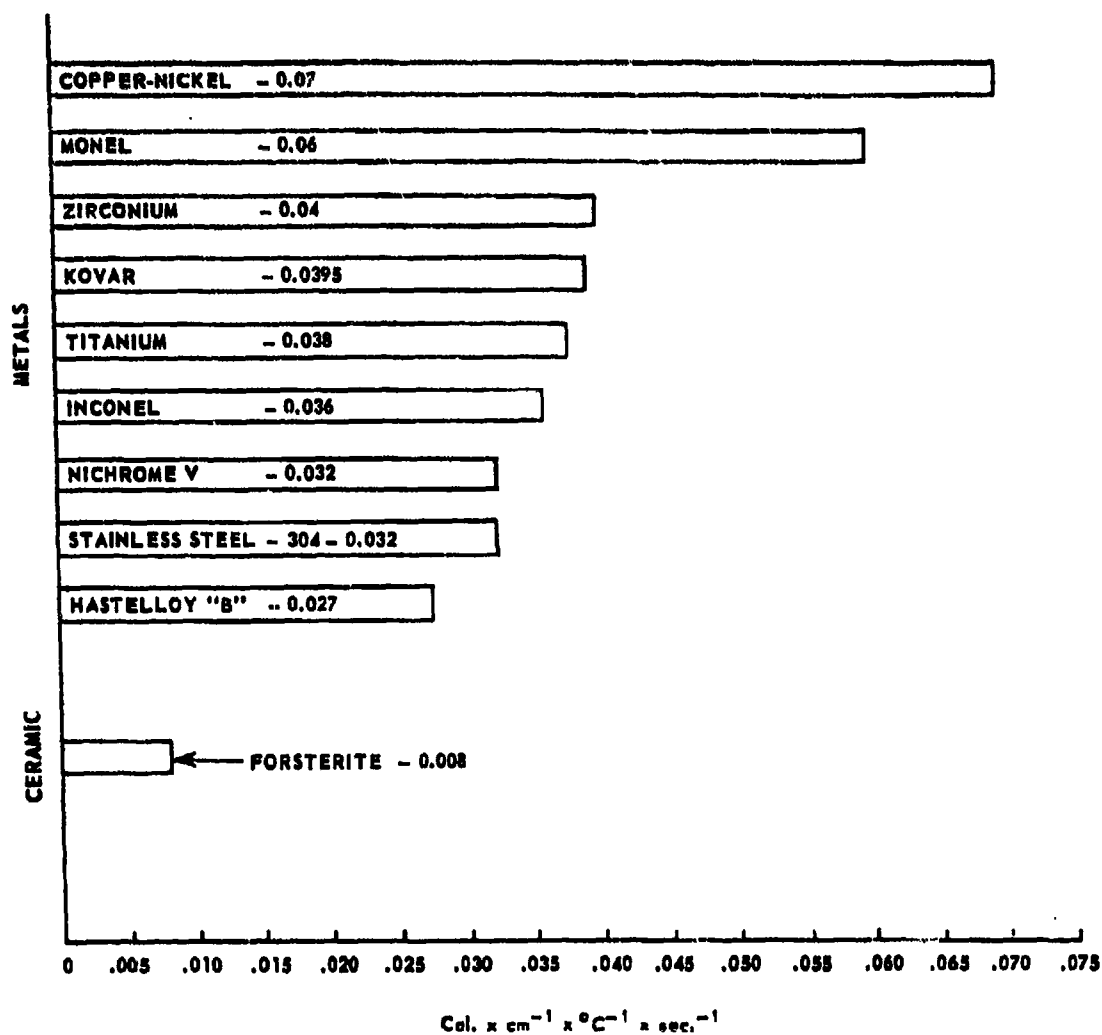


Fig. 84A — Thermal Conductivities of Various Materials

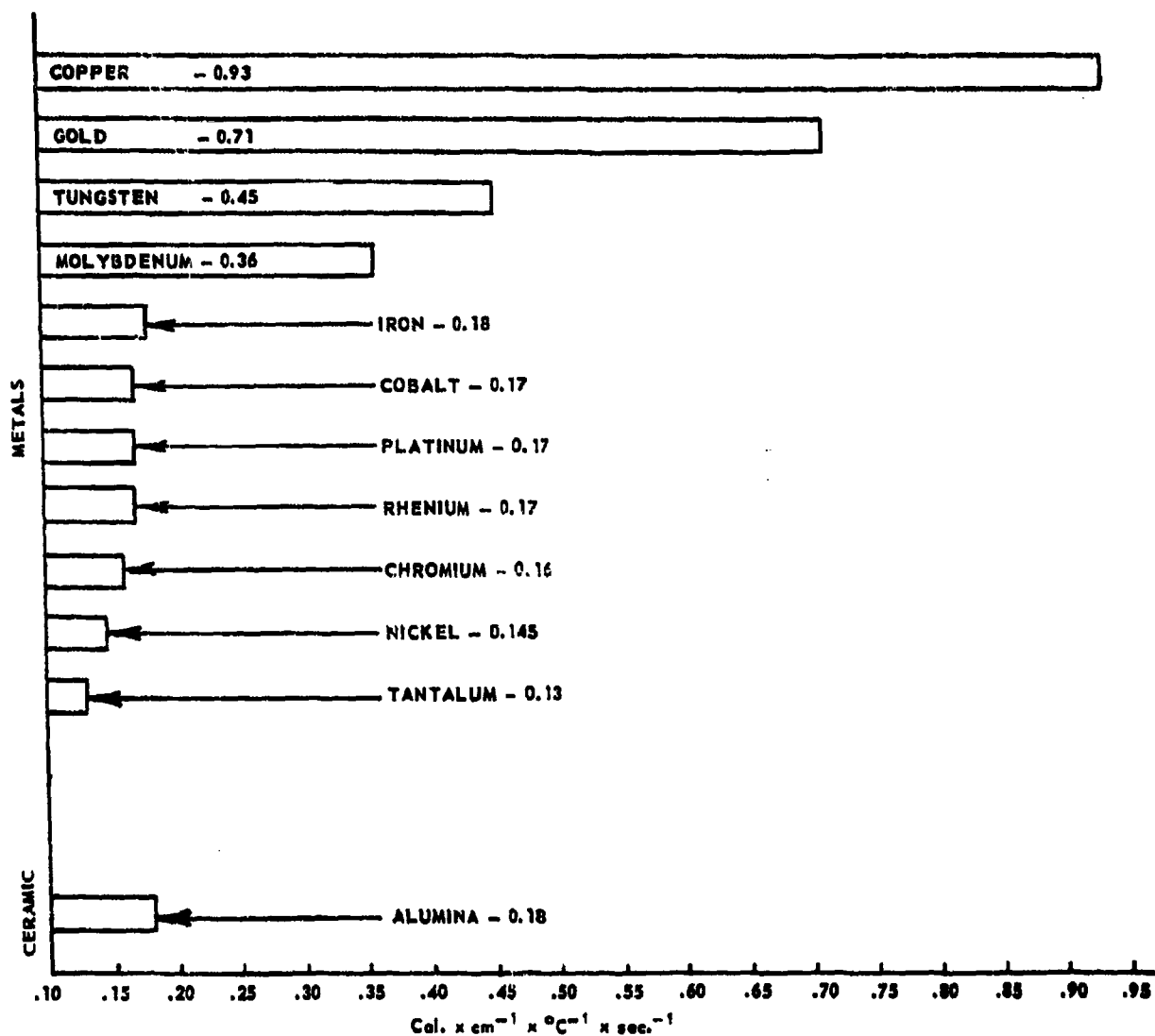


Fig. 84B — Thermal Conductivities of Various Materials

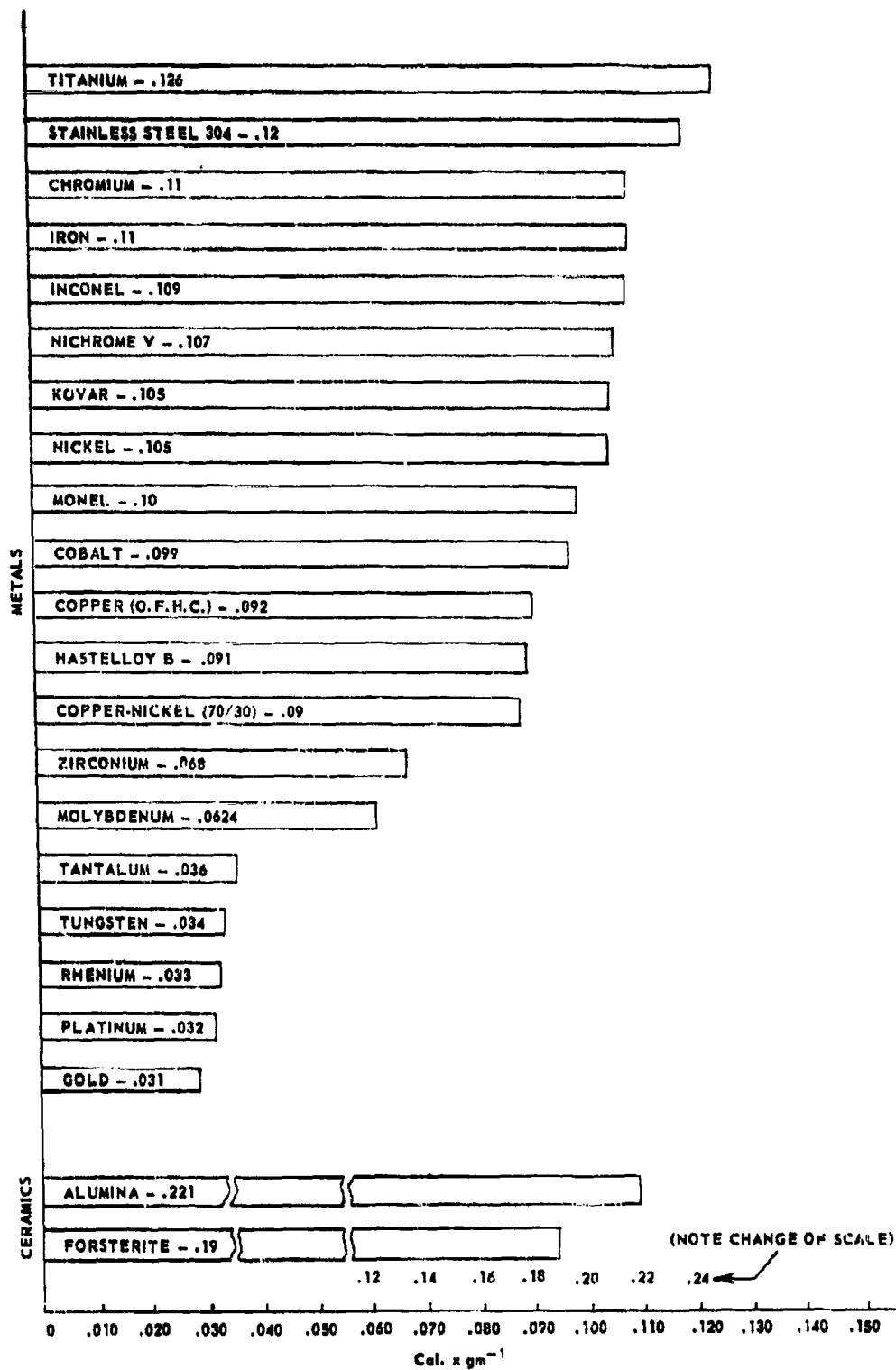


Fig. 85 — Mean Specific Heats for Some Materials Used in Microwave Tube Construction

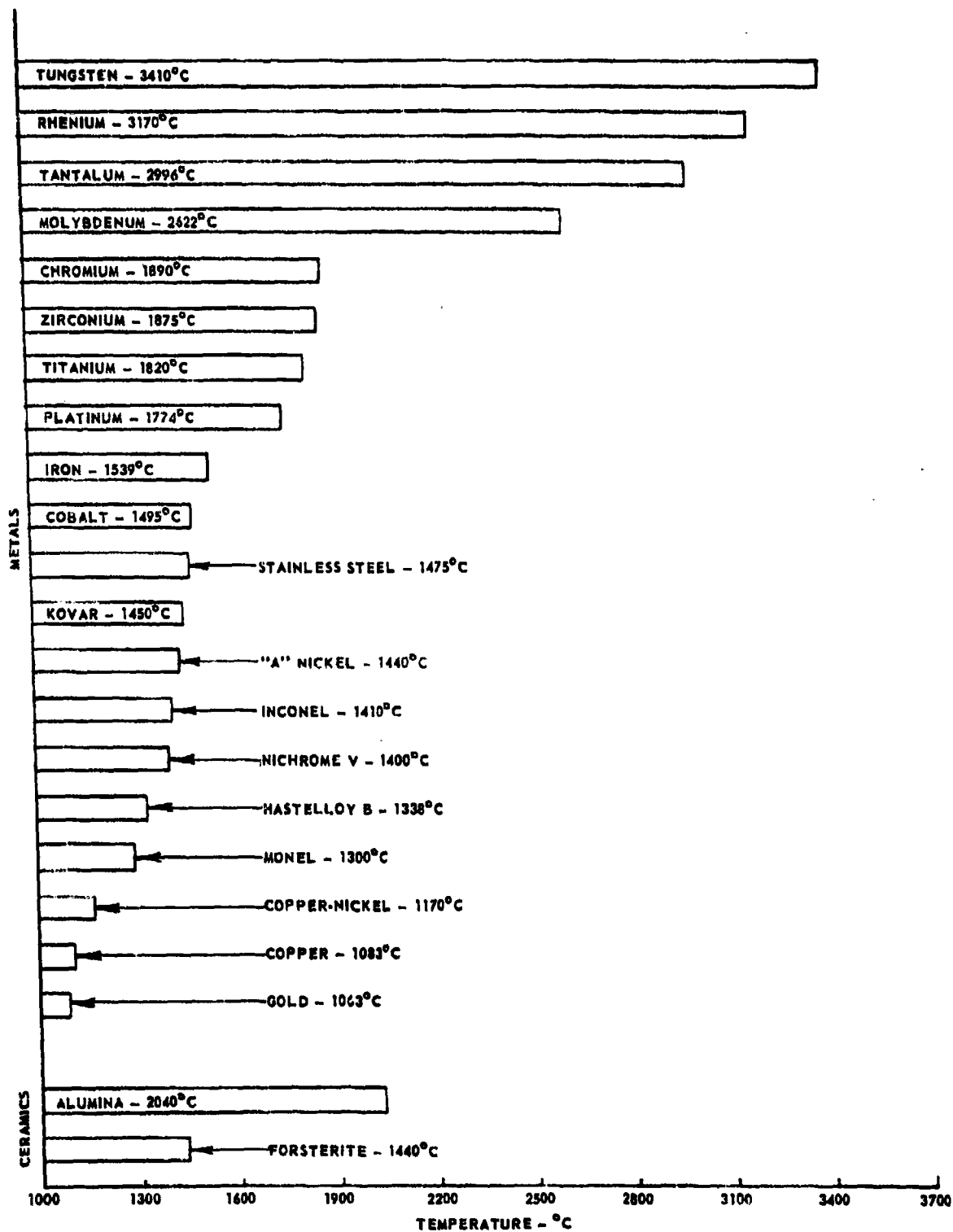


Fig. 86 — Melting Points of Various Materials

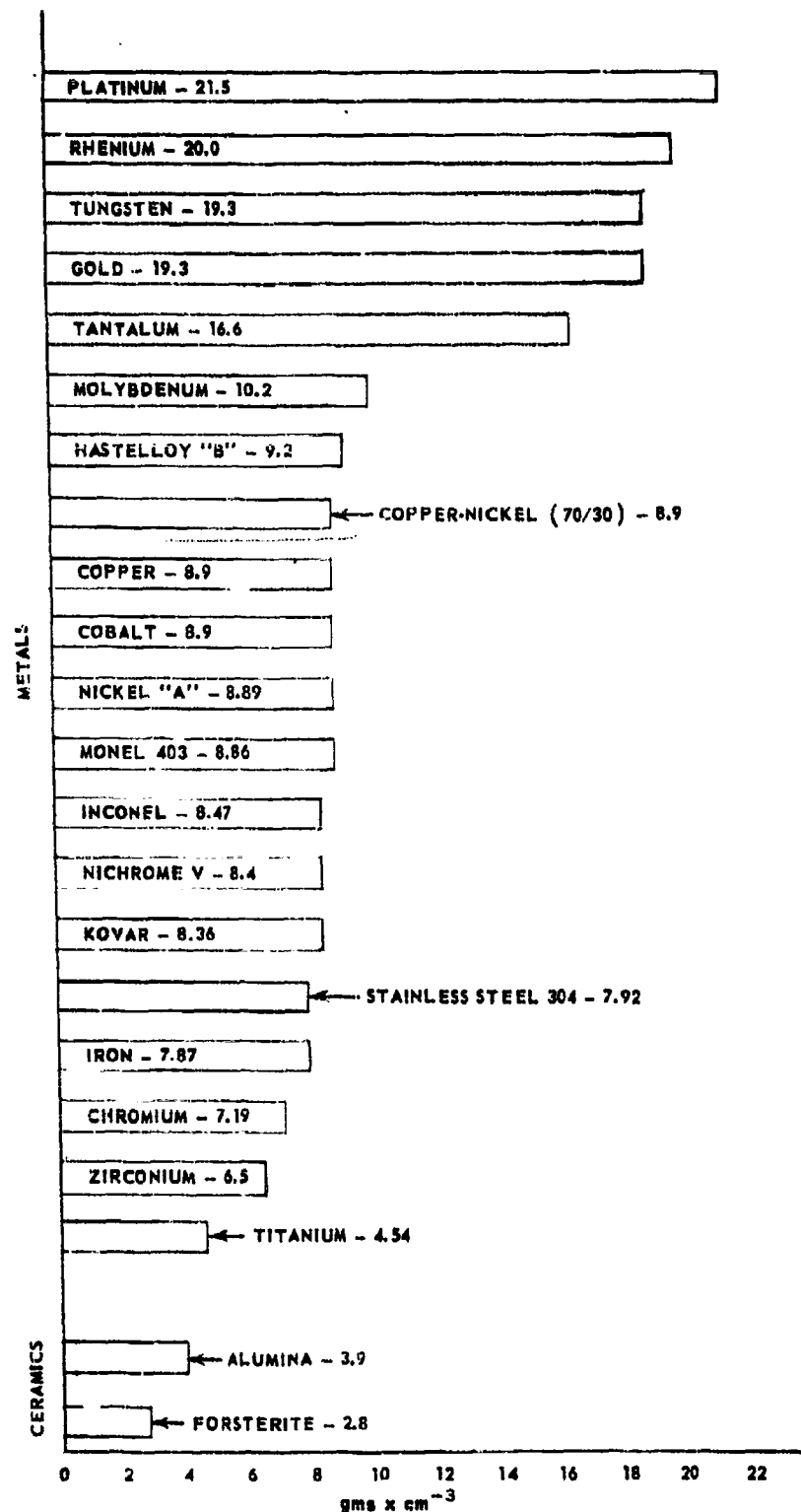


Fig. 87 — Densities of Materials Used in Microwave Tubes

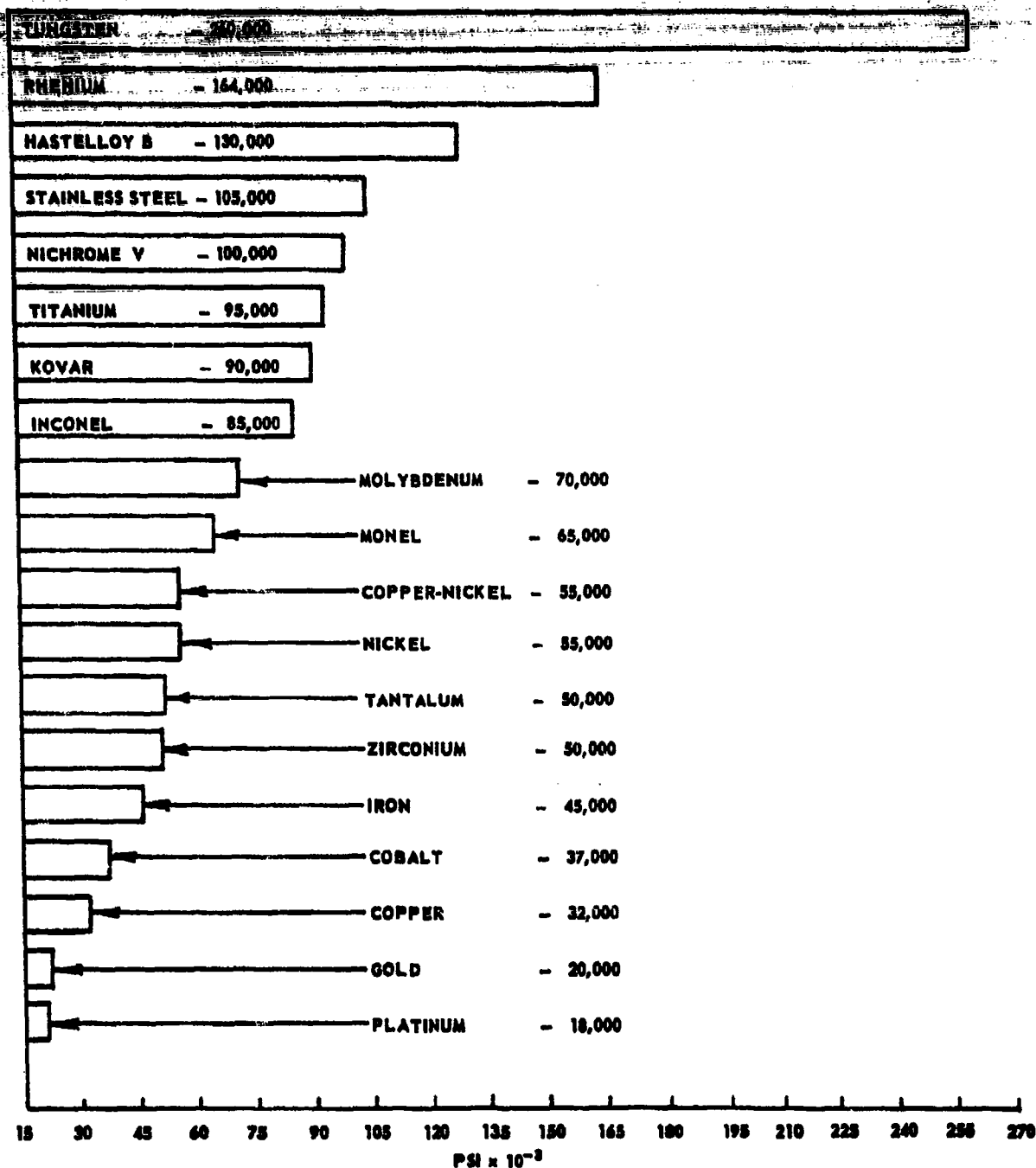


Fig. 88 — Tensile Strengths of Various Materials

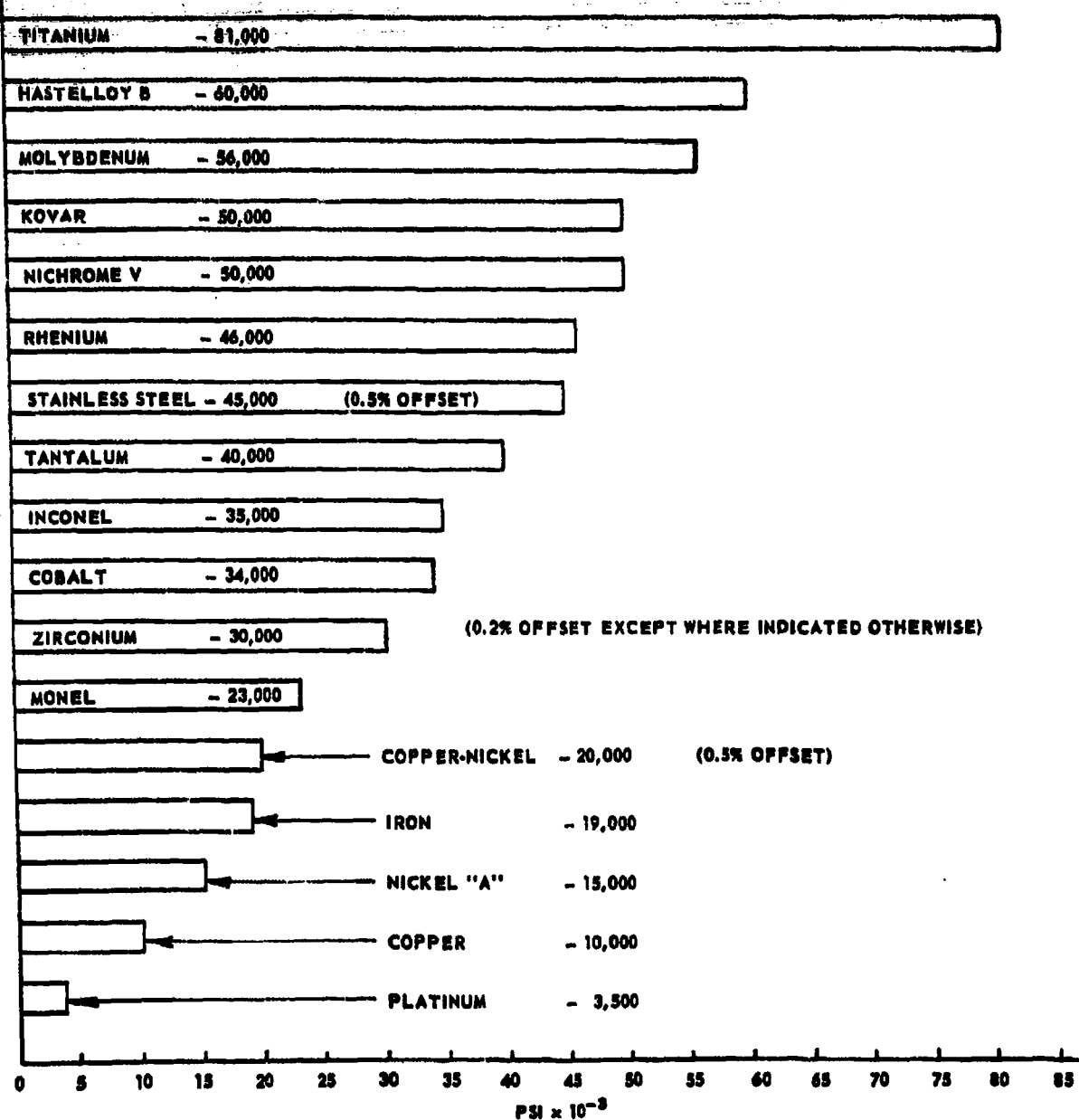


Fig. 89 — 0.2% Offset Yield Strength for Various Materials

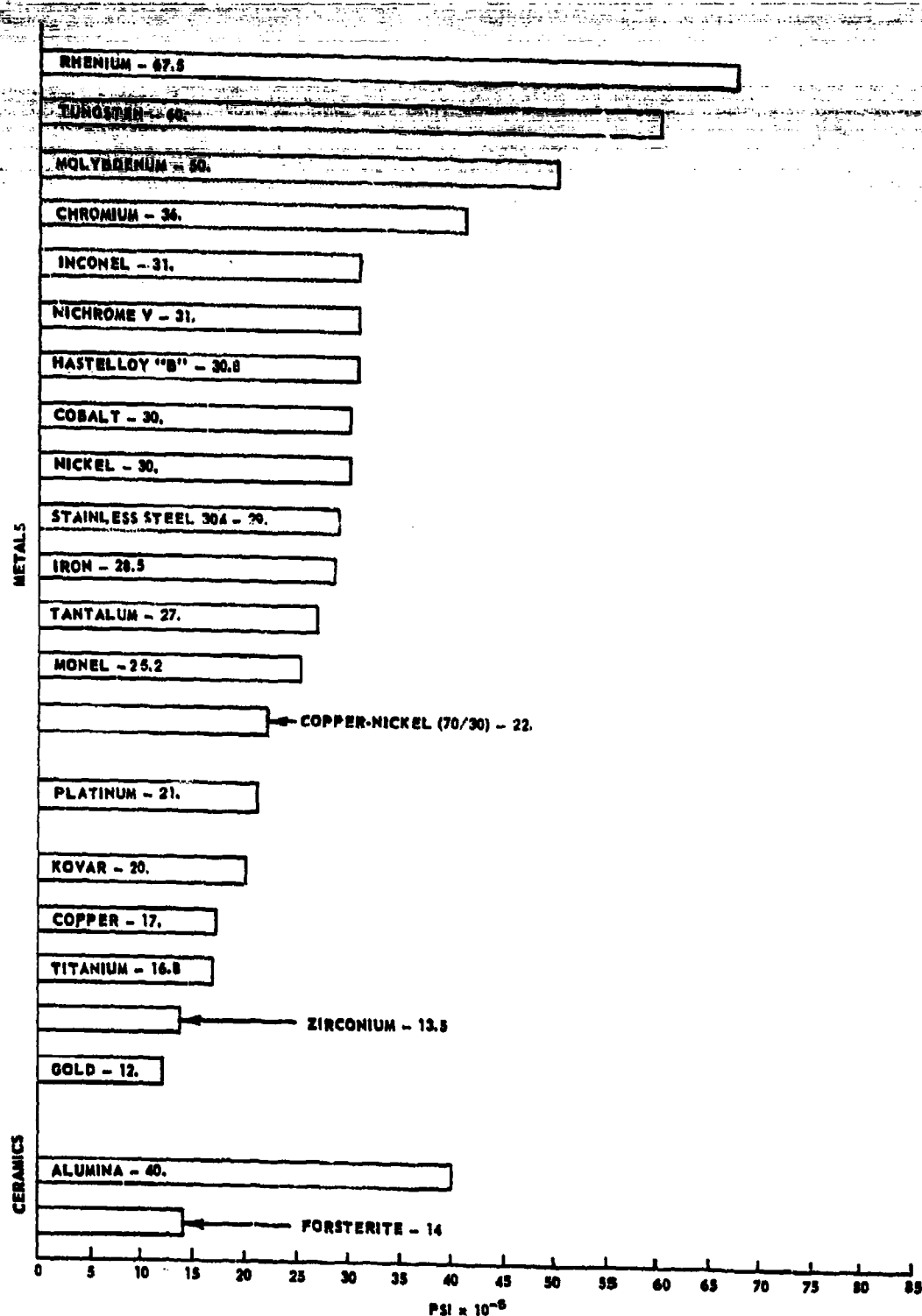


Fig. 90 — Modulus of Elasticity for Microwave Tube Materials

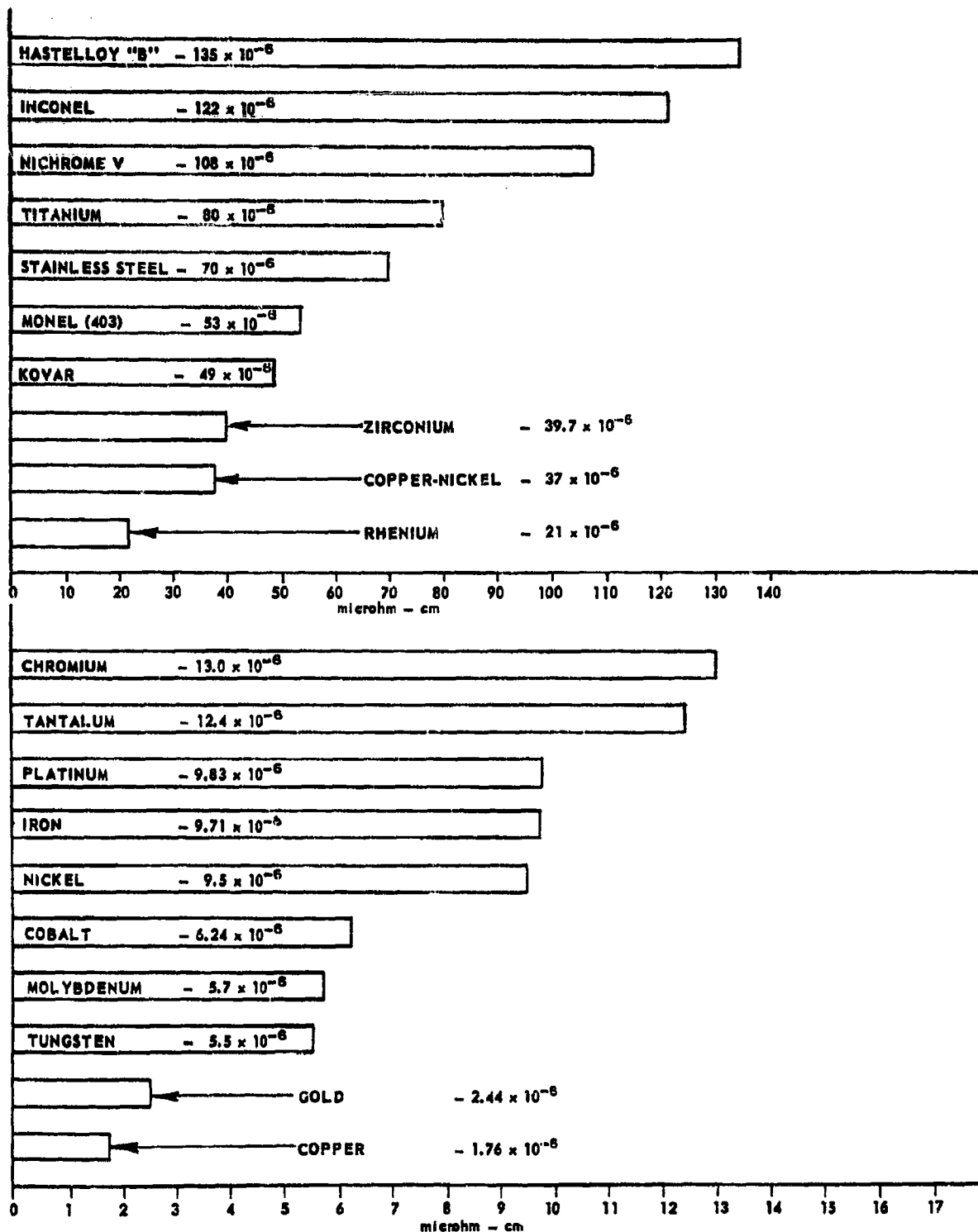


Fig. 91 — Electrical Resistivity of Some Materials Used in Microwave Tube Construction

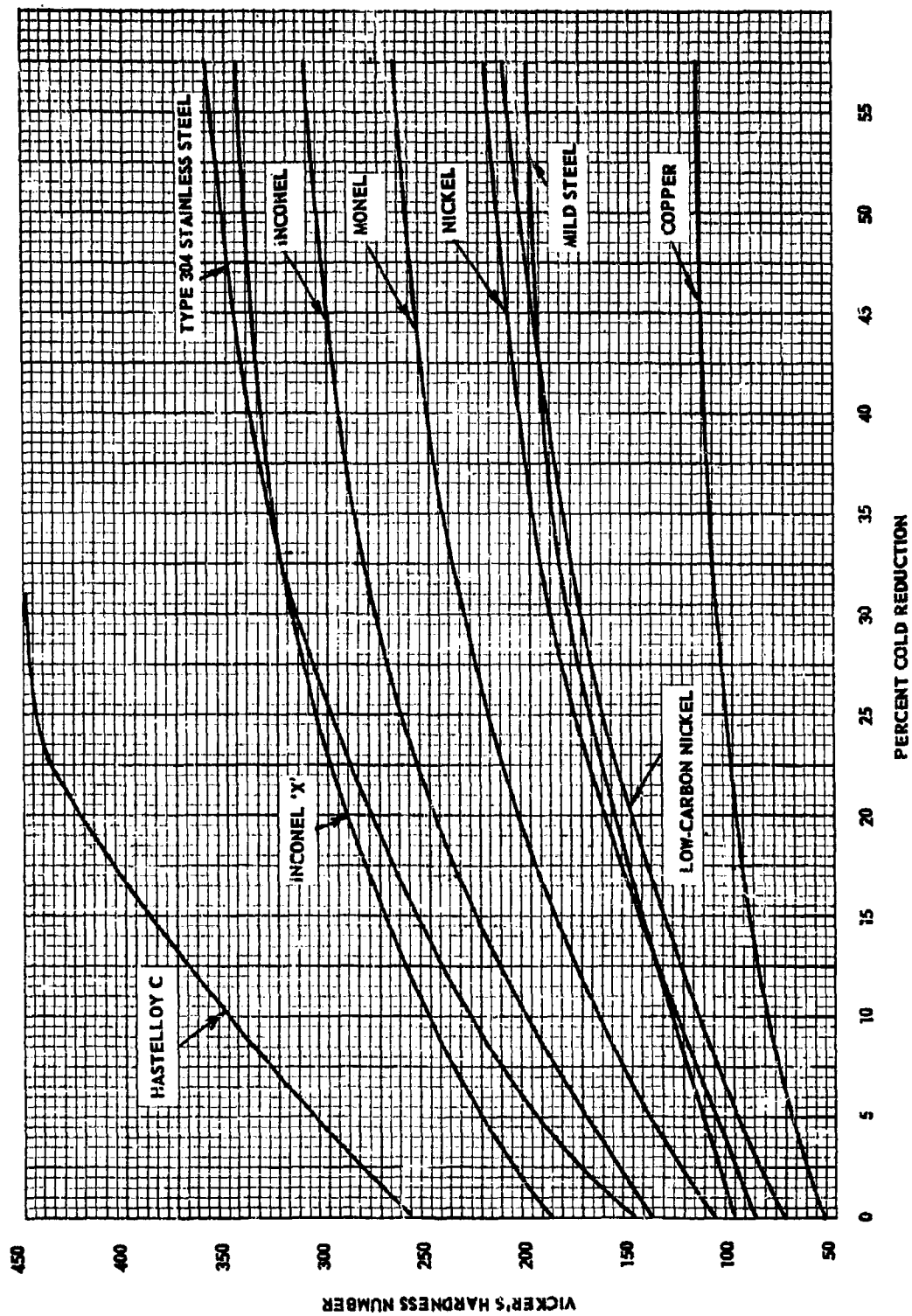


Fig. 92 — Effect of Cold Reduction on Hardness for Various Materials

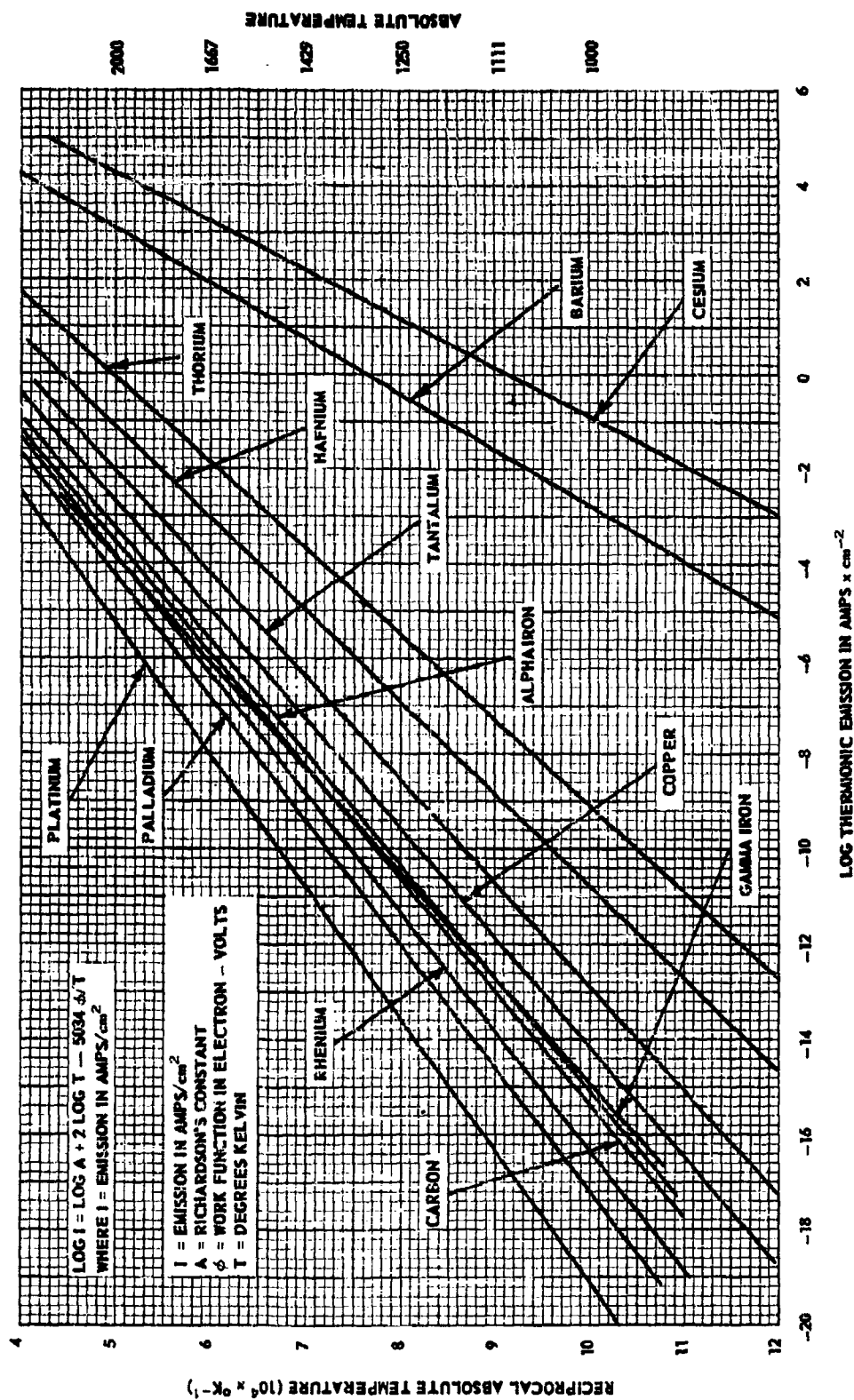


Fig. 93A — Saturated Emission as a Function of Temperature

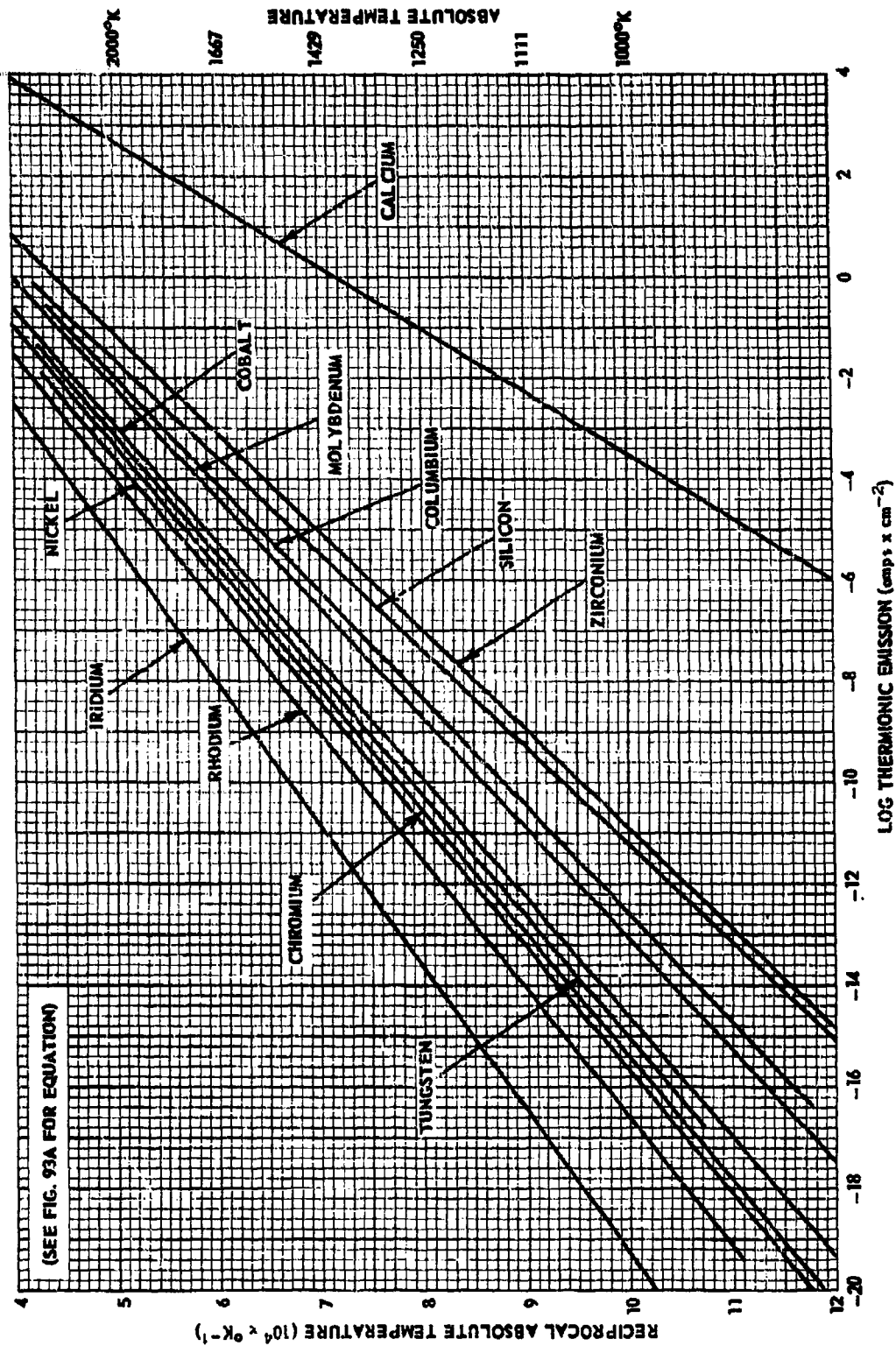


Fig. 93B — Saturated Emission as a Function of Temperature

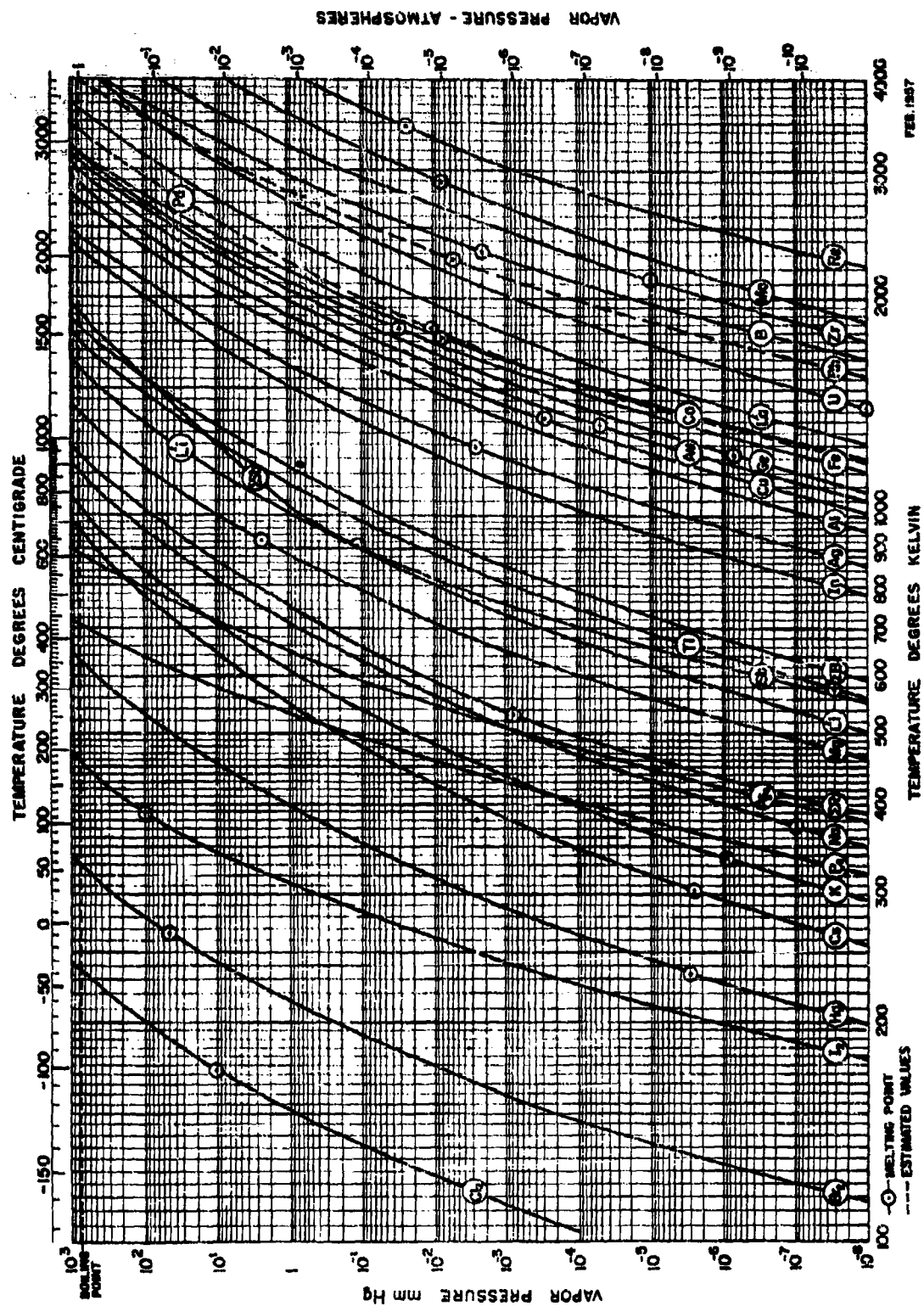


Fig. 94A — Vapor Pressures of Some Elements

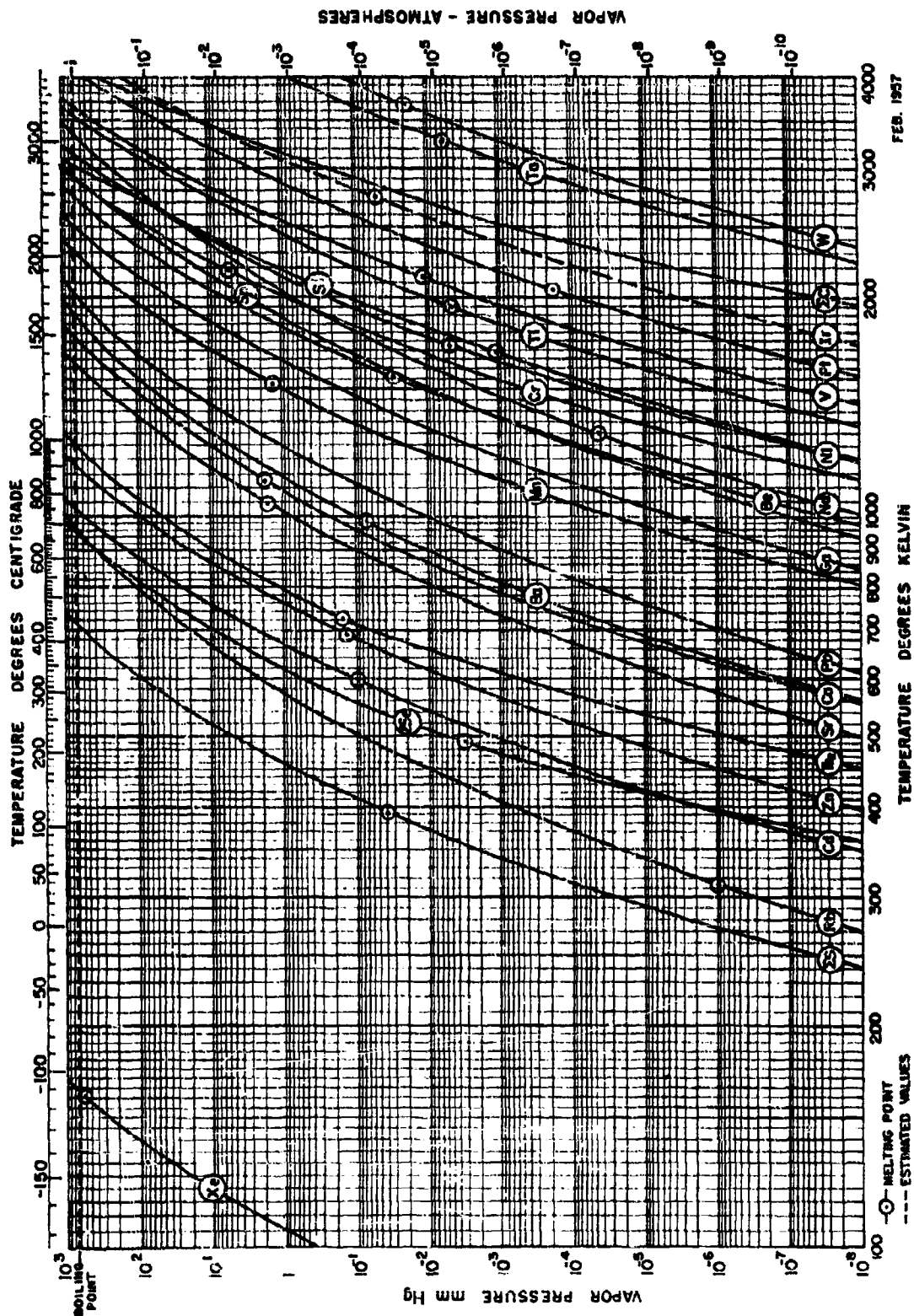


Fig. 94B -- Vapor Pressures of Some Elements

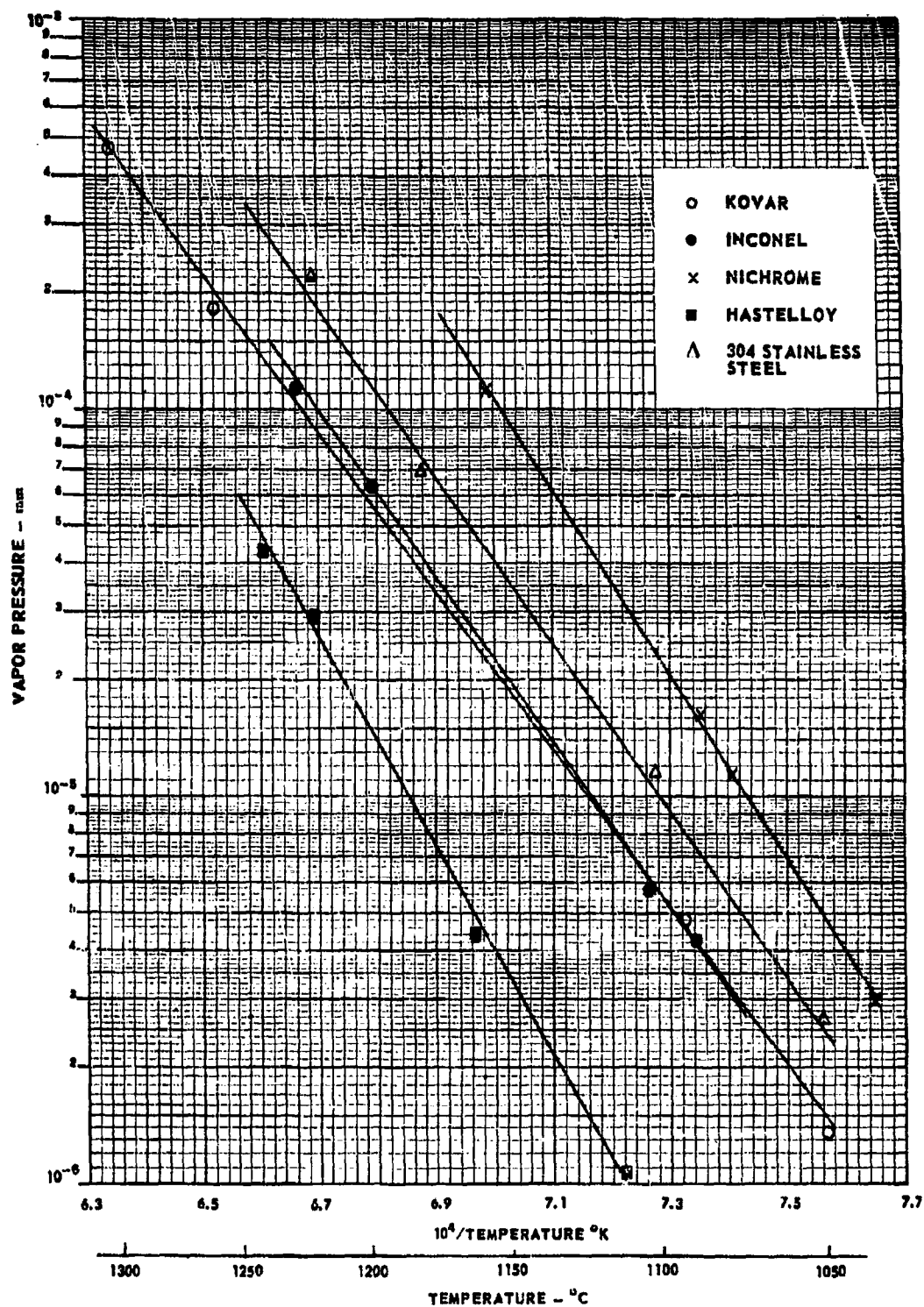


Fig. 95 - Vapor Pressures of Some Alloys

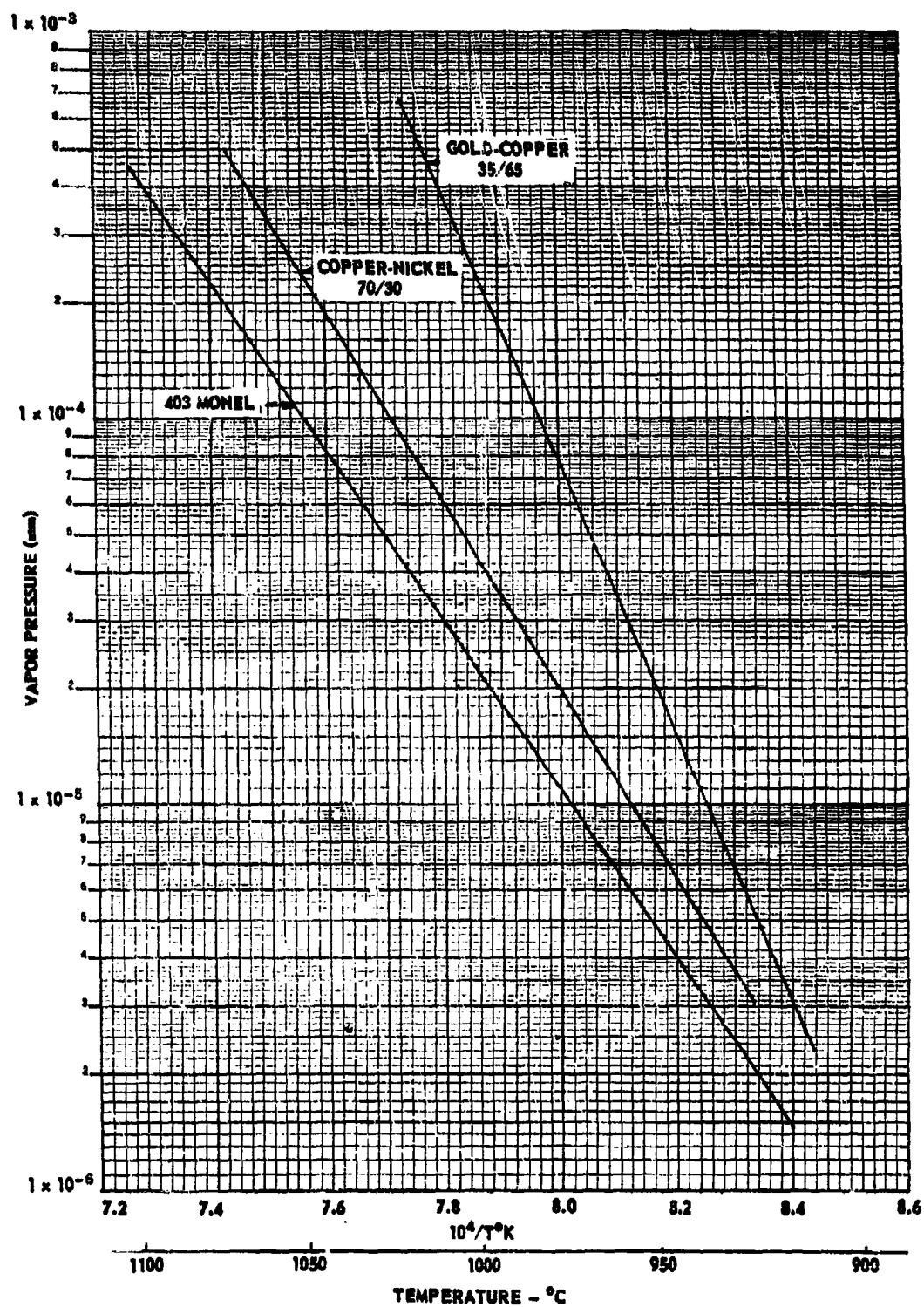


Fig. 96 — Vapor Pressures of Some Copper Alloys

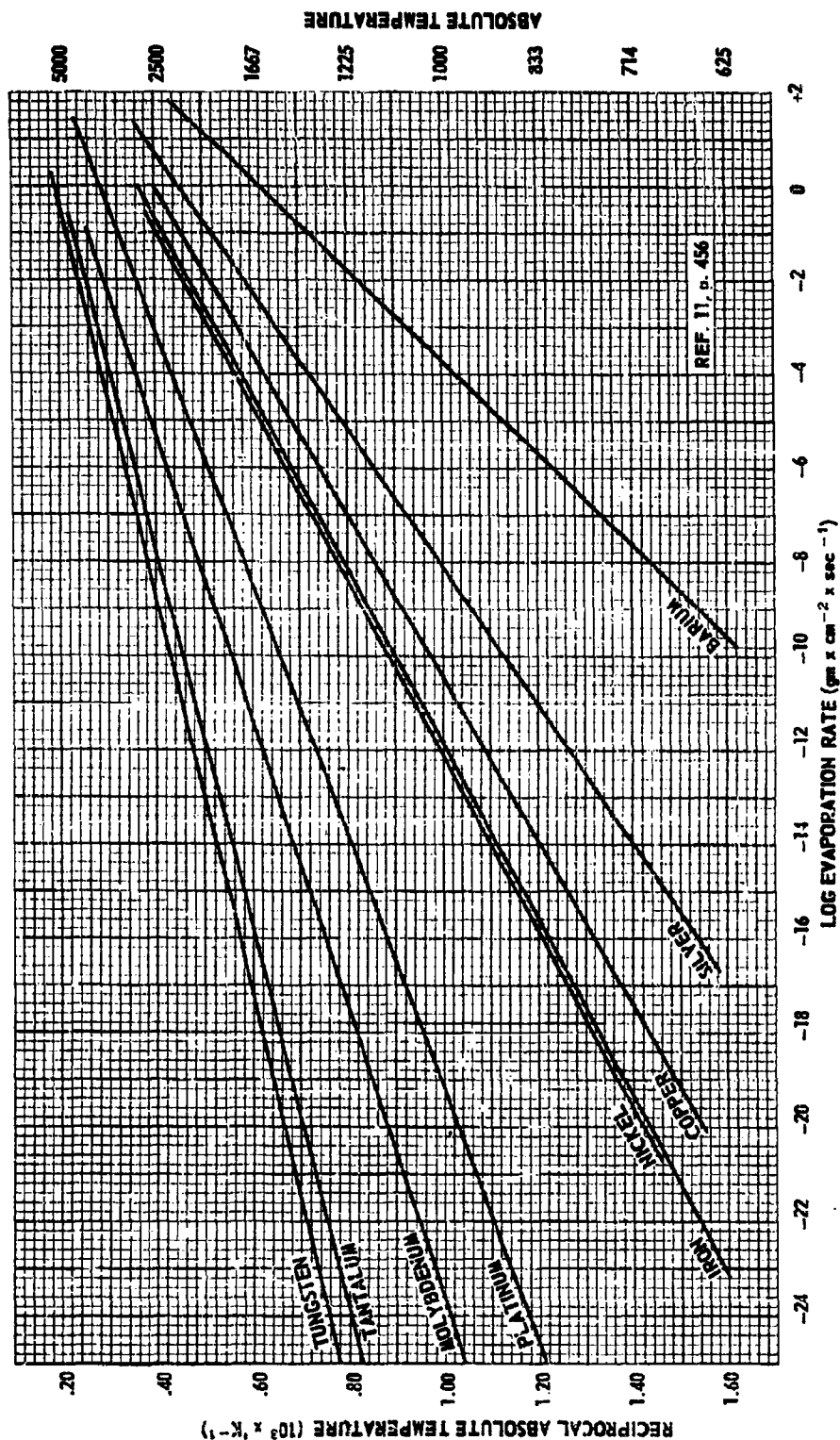


Fig. 97 - Evaporation Rates vs Reciprocal Temperatures for Microwave Tube Materials

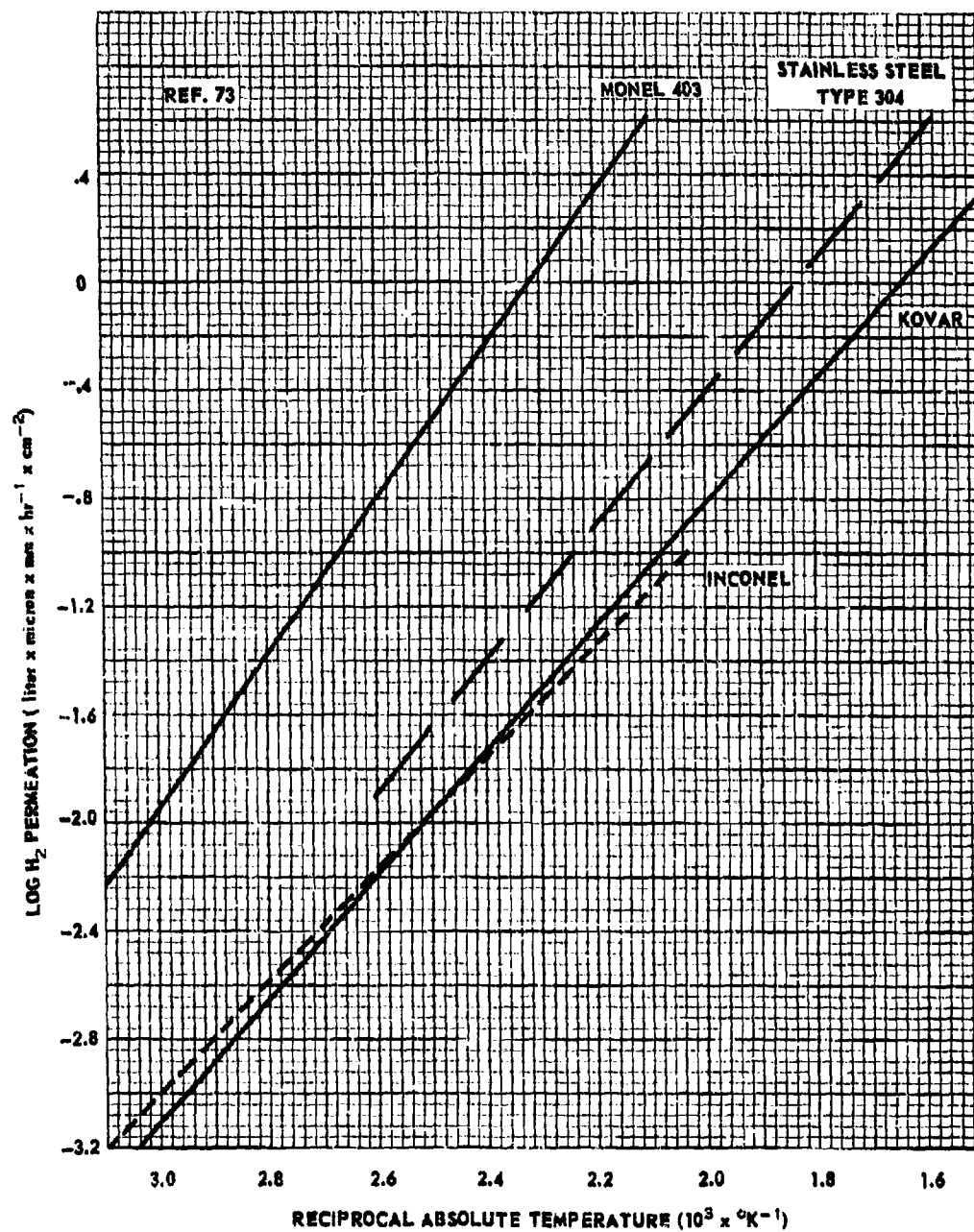


Fig. 98 — Hydrogen Permeation Through Some Alloys

SECTION V

CATHODE POISONING

In this section, each of the major categories of thermionic emitters are described briefly together with information concerning the effects of gases and vapors on the behavior of the cathode. It is well known that for most cathodes, the environment can very seriously affect the cathode performance (emission level and life). The effects of gases on emission have been studied almost as long as phenomena of thermionic emission. In fact, early determinations of emission capabilities of cathodes were limited by the vacua which were attainable at the time.

With present day diffusion and getter-ion pumps it is not uncommon to achieve residual pressures in a tube or exhaust system of the order of 10^{-7} or 10^{-8} mm Hg or even lower in an ultra high vacuum system. The internal environment to which a cathode is exposed during life can, however, still be variable, determined by the choice of materials used in the tube as well as their processing and exhaust. A number of investigators^{85,86} have shown how very greatly dependent were the emission capabilities of the cathode (saturated emission) on the tube materials and processing. With oxide cathodes, for example, there has been much evidence to indicate that the stability and emission level can be limited more by the gaseous environment of the cathode resulting from other tube materials and their processing than by the components of the cathode itself.

This section has therefore been included to describe the effects of poisoning contaminants on cathodes of various types.

A. General Theory

In a solid, the potential energy of an electron is lower than that of an electron in free-space. It is therefore necessary for work to be done to remove an electron from the material. This amount of work (expressed in electron volts) is known as the "work function" and is designated by ϕ . If the solid is a conductor or semiconductor and is heated, some of the electrons, depending upon the temperature and the value of ϕ , may acquire sufficient energy to escape. If there is present a sufficiently high electric field, these electrons will be drawn away as rapidly as they are emitted. This "saturated" condition of thermionic emission is described by the Richardson-Dushman equation:

$$I_s = A_0 T^2 e^{-\phi/kT}$$

where I_s = saturated thermionic emission current in a/cm²

A_0 = constant having a theoretical value of 120 a /cm²/deg²

ϕ = true work function in ev

T = absolute temperature in °K

It can be seen that the most desirable materials will be those with the lowest values of ϕ and the highest values of A_0 . The value of A_0 , in fact, has little effect on the emission capabilities of materials when compared to the large dependence of I_s on ϕ .

The other factor which can effect the emission is T , the temperature. Like ϕ , this will sensitively affect the saturated emission level. A practical limitation exists, however, to the usefulness of many materials which on the basis of their low work function would otherwise appear to be superior as thermionic emitters. These are the materials which have

prohibitively high vapor pressures at the temperatures required for significant levels of emission. It is for this reason that metallic caesium, despite its low work-function value 1.9 ev, is a much poorer cathode material than tungsten or tantalum with work functions of 4.5 and 4.1 ev, respectively. Wright⁸⁵ has compared the vapor pressure as well as the work functions of pure metals and derived a meaningful figure of merit by dividing work function at 0°K, ϕ_0 , by the absolute temperature at which the vapor pressure is equal to 10^{-5} mm Hg. When compared under these conditions caesium is found to have a figure of merit of 5.9×10^{-3} as compared to values for tungsten and tantalum of 1.6 and 1.5×10^{-3} , respectively (lower values are preferred).

B. Pure Metal Cathodes

A careful examination of the work functions and figures of merit of the elements indicates that the four metals which have the lowest figures of merit are tungsten, tantalum, hafnium and rhenium. Of these materials, tungsten and tantalum have found important commercial applications as cathodes.

A pure metal cathode is used commercially in applications where the cathode is subjected to high-energy ion-bombardment as may be the situation for tubes operating at anode voltages of more than 4000 to 5000 volts above the cathode potential (other cathode types can be deactivated and stripped of their coatings under severe ion-bombardment). Under high fields, gas molecules as positive ions are projected into the cathode at velocities often high enough to remove some of the surface material. An oxide layer or monatomic metal film, such as thorium or barium, will be rapidly removed under these conditions. A pure metal, however, could lose only its

outer metallic surface exposing a fresh surface of the same material. The ultimate end of life would therefore be realized when the cathode has been eroded through its entire thickness.

Because of the very high temperatures required for pure metal emitters indirect heating with separate heater elements cannot be considered. These cathodes are most commonly heated directly by passing currents through filaments or cylinders of the material. These cathodes have also been heated by methods employing electron-bombardment.

If a tungsten filament is cleaned of adsorbed impurities by flashing for a short time at 3000°K ., the thermionic emission can be measured at temperatures as low as 1400°K .. If the partial pressure of gases capable of being adsorbed on the filament is greater than 10^{-10} mm., the thermionic emission will decrease with time.⁸⁷ This is characteristic of the adsorption of electro-negative gases such as oxygen or water vapor. Tungsten emission is also impaired by nitrogen although it is not appreciably affected by mercury vapor or the rare gases.

The effects of the gases upon pure-metal thermionic emission have not been studied to the extent that adsorbed layers of electro-positive atoms have been investigated. These electro-positive films are considered below.

C. Thin Film Emitters

Electro-positive adsorbed films on the surface of a metal such as tungsten have the effect of lowering the work function of the surface. On tungsten, a thin film of elemental thorium or barium is held tenaciously

by the surface binding forces thereby resulting in the lowering of the effective vapor pressure (or evaporation rate) of the film. It is somewhat difficult to obtain representative values for the emission constants for the Richardson-Dushman equation since these depend largely upon the condition of the metallic surface, grain orientation, and the fraction of the surface covered by the film. Thorium or barium will, however, lower the work function of the cathode to values below those of either tungsten or of the adsorbed metal. Two types of film emitters, thorium on tungsten and barium on tungsten are considered separately below.

1. Thorium on Tungsten

The presence of a film of thorium on tungsten can lower its work function from 4.54 ev to as low as 2.7 ev (thorium metal itself has a work function of 3.4 ev). Thoriated tungsten filaments are made from tungsten to which 1% of thorium has been added at the metal powder or oxide stage. Free thorium is formed by first heating the filament to $2600^{\circ} - 2800^{\circ}\text{K}$. This is followed by an aging period at $2100^{\circ} - 2300^{\circ}\text{K}$ to allow the establishment of a stable monatomic film. This film will remain stable at the operating temperatures of $1800^{\circ} - 2000^{\circ}\text{K}$ provided a very good vacuum is maintained. The presence of residual gases can result in a loss of some of the film both by positive ion bombardment and reaction of the film with the gas. It is thus essential that this surface film can be replaced. This is achieved by the dispensing action resulting from diffusion of thorium along grain boundaries of the tungsten. Under ideal conditions, a balance is maintained between the arrival rate of thorium at the surface and the rate of loss from the surface. If, as is often the case, the vacuum is

poorer than is required for stable operation of this film this condition can be improved considerably by first carburizing the outer layer of the tungsten. By heating the filament in a hydrocarbon vapor at 2000° - 2500°K a carbide skin can be formed on the surface. This carbide can reduce thorium in the ordinary operating range of the cathode, thereby, enabling it to replenish thorium at the surface and maintain emission under conditions of higher gaseous levels. The lives of these cathodes can be many thousands of hours.

2. Barium on Tungsten

As for thorium, a film of barium can also lower the effective work function of a tungsten surface; values of 1.6 ev have been observed (metallic barium has a work function of 2.5 ev). Because of its lower work function this cathode can provide satisfactory emission levels at temperatures of 950° - 1200°C . A number of cathodes have been developed and used commercially which utilize barium films on tungsten.⁸⁸⁻⁹² Since elemental barium has relatively high vapor pressures at the temperatures of cathode operation, it is necessary to provide an ample reserve of barium or a compound which can generate the free metal, as well as a mechanism for dispensing the barium to the surface at the desired rate. Lemmens, Jansen, and Loosjes⁸⁸, in 1950, described a cathode which employs a pellet of alkaline-earth oxides enclosed within a porous tungsten sponge of controlled porosity and sealed in a molybdenum housing. This has been superseded by improved versions in which the tungsten sponge itself was impregnated with barium aluminate⁸⁹ and barium-strontium aluminates.⁹⁰ The impregnated versions can be assembled more easily and can be processed

without evolution of excessive amounts of gases. In still another version,⁹² powders of molybdenum-tungsten alloys were molded directly with powders of barium-calcium aluminate into cathode pellets and sintered in vacuum or hydrogen.

Several studies have been made of the poisoning effects of gases or metal vapors on matrix cathodes.^{73,93,94} Oxygen and carbon dioxide were found to poison emission severely, especially at the lower temperatures of cathode operation and at pressures above 10^{-7} mm. Carbon monoxide at the lower pressures affects emission little or even improves it slightly; at higher pressures in the range of 10^{-5} mm, carbon monoxide behaves as a poison of the emission. Brous, et al.,⁷³ have also observed significant poisoning effects by hydrogen and nitrogen; this was not found for these gases by Jenkins and Troddon.⁹⁴ Air was also observed to poison but not as intensely as would be anticipated in consideration of its oxygen content.

Metal vapors, such as platinum, palladium, cobalt, nickel, iron, titanium zirconium, chromium and molybdenum, poison the emission of a matrix cathode while copper and gold do not.^{73,95} This is apparently dependent upon the relative vapor pressures of the contaminant metals and how strongly they are held to the surface by alloying. Gold and copper which do not alloy with tungsten and which have relatively high vapor pressures at the temperatures of matrix cathode operation, were found not to affect emission.

A number of researchers have demonstrated that the surface film of the matrix cathode is not simply an elemental barium monolayer but rather a semiconducting film or even a layer of semiconducting oxide.⁹⁶⁻⁹⁸ This

film or layer which is extremely thin is not, however, identical in its properties or behavior to an oxide cathode.

D. Compounds

Since the discovery of the oxide cathode by Wehnelt in 1903, compounds have been used successfully as thermionic emitters. For a compound to be of any practical value it must have the following properties:

- (a) chemical stability at the temperature of operation or,
- (b) any decomposition must proceed slowly, liberating products which do not adversely affect emission.
- (c) low volatility
- (d) fairly high melting point
- (e) conductive or semiconductive properties at the temperature of operation

Since the number of compounds which could be considered for use as thermionic emitters is almost without limit, one could imagine that a very wide variety of compound emitters would be encountered. In practice, consideration is limited to oxides although other compounds, such as carbides, nitrides and borides, have shown much promise as thermionic emitters.

1. Alkaline Earth Oxides

Alkaline earth oxides at the present time are commercially the most widely used emitters. Although discovered in 1903⁹⁹ and since then intensively studied and improved, these cathodes are still the subject of much additional study and improvement. The oxide coatings are n-type semiconductors which appear to have an excess of neutral barium atoms distributed interstitially in the lattice. Most of the theories of oxide

cathode mechanisms indicate that free barium is released by chemical reduction by trace impurities present in the base metal, as well as by thermal and electrolytic decomposition of the oxide. This barium can then diffuse into the crystal lattice and over the internal and external surfaces, imparting the desired properties of conductivity and low work function to the coating.

Very careful attention must be given to the choice of the base metal and oxides as well as the other materials and tube processing. This is to assure that a regulated supply of activators will be dispensed to the coating over tube life and minimum levels of electro-negative contaminants will be present in the cathode environment. Descriptions of the many considerations given to the design and processing of an oxide cathode have alone been the subjects of entire books.¹⁰⁰

The cathode, as is well known, is subject to poisoning of various types. This is caused by reaction of the free barium with oxidizing gases, such as oxygen and carbon dioxide. Carbon monoxide at low pressures enhances emission slightly but poisons at pressures greater than 10^{-4} mm Hg. Halogens and their ions react with the free barium and the oxide coating forming volatile halides, reducing cathode life and emission. Sulfur or sulfur-bearing gases also react with the free barium. Water vapor reacts with the coating to form the hydroxide which has a low melting point. This can result in shrinkage of the coating and bare spots on the base metal. Hydrogen or the inert gases do not poison the emission.

When operated at high plate dissipation the emission is often observed to "slump". This is attributed at least in part to emission poisoning by

contaminants evaporated from the anode. Changing the anode to a tungsten structure and outgassing more vigorously will usually reduce or eliminate this effect. It is for this reason that the highest saturated emission levels are realized under pulsed conditions where the plate dissipation is kept low, using low repetition rates and narrow pulses. Water cooled cathodes can also reduce cathode contamination by anode impurities.

2. Thoria

Coatings of thoria on tungsten or tantalum have also found commercial application. Compared to barium oxide it has the following advantages:⁸⁵

- (a) It is more refractory
- (b) It has a lower electrical resistance at its operating temperatures
- (c) It does not form high resistance interface compounds with tungsten or tantalum
- (d) It is less subject to arcing
- (e) It is easy to activate and less easily poisoned

Its chief disadvantage is its high operating temperature (1900° - 2000°K) necessitating direct or bombardment heating. Another disadvantage is the high rate of erosion resulting from coating electrolysis. In early work, self-supporting sleeves of thoria were used. These were indirectly heated. Further work led to the development of directly heated thoria cathodes in which the thoria was admixed with refractory metal powders to increase the conductivity of the cathode. The life of thoria cathodes is often limited by the electrolytic action which can generate free thorium more rapidly than required to sustain optimum cathode emission. In practical applications, the emission should therefore be held to 1 a/cm². Because of the more rapid rate of generation of the free electropositive metal, thoria cathodes are

more resistant to poisoning than oxide cathodes. They will, however, be poisoned by oxygen at 10^{-6} mm Hg, according to Weinreich.¹⁰⁵ Danforth found that the thorium emitter was completely insensitive to gas pressures of 10^{-5} to 10^{-4} mm Hg. The gases present were, however, not specified.

3. Other Compounds

Compounds other than oxides have been studied for their potential applications as thermionic emitters. The borides, carbides and nitrides have shown some promise as usable emitters.¹⁰³⁻¹⁰ Lanthanum boride, in particular, was found by Lafferty¹⁰⁶ to give an emission current of 10 a/cm² at a temperature where its evaporation rate is 10^{-5} g/cm²/sec. It has a figure of merit of 1.27×10^{-3} and a work function of 2.66 eV. This cathode emits copiously at 1300° - 1800°K and can yield 10 a/cm² in a continuous operation. It is stable at room temperature in air and is easily activated at 1800° - 1900°K at which temperature the cathode is also degassed. Carter and Wood¹⁰⁷ found that the presence of nitrogen enhanced the emission. The behavior of a lanthanum boride cathode is in many respects similar to that of a thorium coated cathode, however, it runs at least 200°C cooler than the latter. The evolution of carbon monoxide and hydrogen should be considerably lower than that of the oxide cathode. These cathodes are useful in applications where high current densities are required and for high voltage applications because of good resistance to positive ion bombardment. They are also valuable in denouable systems since they are stable in the atmosphere and activate easily. Lanthanum boride cathodes show great promise for more widespread application.

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